PB 179514

Water Pollution Control Research Series

# A STUDY OF SLUDGE HANDLING AND DISPOSAL

U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration

PUBLICATION WP-20-4

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# A STUDY OF SLUDGE HANDLING AND DISPOSAL

By

R. S. Burd

This Study was supported in
part by Grant No. PH 86-66-32
while Mr. Burd was with the
Dow Chemical Company.

U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration
Office of Research and Development

May 1968

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Water Pollution Control Research Series Publication No. WP-20-4

## Foreword

Sludge handling and disposal have often been called the most troublesome aspect of water and wastewater treatment. If this is true, it is unfortunate that researchers and design engineers have in recent years neglected sludge handling in favor of the more glamorous problems associated with the liquid portion of wastewaters.

In anticipation of a renewed search for new sludge handling techniques, the Dow Chemical Company and the Federal Water Pollution Control Administration agreed that the status of the sludge handling art should be reviewed. Researchers and design engineers could then use the comprehensive report as a basic reference for new exploration. Many sludge handling techniques have been tried in the past and many different techniques are in use today. But, until this report was prepared, no accurate and complete documentation of sludge handling processes was available.

The Dow Chemical Company has been studying the many facets of sludge handling for years, partly as an adjunct to sludge disposal from its own waste treatment facilities and partly because the company has been developing commercial products for sludge conditioning. This latter has resulted in sludge handling investigations at hundreds of waste treatment facilities from coast to coast. The investigations enabled the Company to propose valid new approaches and to summarize the status of past and present activity.

This report is considered to be complete, accurate, and of practical value to many people. A very thorough literature survey was followed by numerous field interviews which accomplished two objectives: 1) they provided a check on the accuracy of published data and 2) they provided the most up-to-date information.

Some technical details have been omitted because they exceeded the study's objectives. The bibliography includes more than 450 references containing additional details on any specific unit process. Detailed theory of sludge handling unit processes can be secured from these technical papers. Nevertheless, this report contains as much detail as was practicable, without its becoming too bulky for use as a reference document.

Water plant sludge handling is discussed in less detail than wastewater sludge because little has been written about the former and it has not been as troublesome as wastewater sludge handling.

The report suggests items for further study as well as describing the current state of the art. It is offered to researchers, design engineers, equipment manufacturers, owner-operators of treatment facilities, and regulatory personnel as a basic and practical guide to sludge handling and disposal. The Federal Water Pollution Control Administration has accepted the report in fulfillment of the Dow Chemical Company contract obligation.

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## Sludge Handling and Disposal Report

### Key Words

Sludge handling
Sludge disposal
Sewage treatment
Water treatment
Industrial waste treatment
Wastewater treatment
Sludge
  Combustion
  Composting
  Concentration
  Conditioning
  Dewatering
  Digestion
  Disinfection
  Drying
  Elutriation
  Incineration
  Lagooning
  Land disposal
  Ocean disposal
  Odor control
  Pipeline transportation
  Recovery
  Thickening
  Utilization

## ACKNOWLEDGEMENTS

In addition to information from the literature, the author gratefully acknowledges the assistance of contributors representing the organizations listed below.

Allegheny County Pa., Sanitary Authority
Bartlett-Snow-Pacific, Inc.
Black and Veatch Consulting Engineers
California State Health Department
Camden, New Jersey, Sewage Treatment Plant
Chicago Metropolitan Sanitary District
Consoer and Townsend Consulting Engineers
Dorr-Oliver, Inc.
Dow Chemical Company
East Bay Municipal Utility District (Calif.)
East Cliff-Capitola Sanitary District (Calif.)
Eimco Corporation
Hayward, Calif., Sewage Treatment Plant
Hershey Estates, Pa.
Kirkham, Michael and Assoc., Consulting Engineers
Los Angeles County Sanitary District
Los Angeles Hyperion Sewage Treatment Plant
Middlesex County, New Jersey, Sewerage Authority
Midland, Michigan, Sewage Treatment Plant
Milwaukee Sewerage Commission
National Canners Association
National Council for Stream Improvement
New York City Dept. of Water Pollution Control
Nichols Engineering and Research Corp.
University of North Carolina, Dept. of Sanitary Engineering
Quirk, Lawler and Matusky Consulting Engineers
San Diego Utilities Dept.
S. San Francisco Sewage Treatment Plant
Stanford University
Tillo Products, Inc.
U. S. Public Health Service
Walker Process Equipment, Inc.
Washington D. C. Dept. of Sanitary Engineering
*Water and Sewage Works Magazine*
Westchester County, New York, Dept. of Public Works
Roy F. Weston, Inc., Consulting Engineers
Whitman, Requardt and Assoc. Consulting Engineers

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REFERENCES

# SLUDGE HANDLING AND DISPOSAL

## Abstract

This report discusses in detail the broad subject of water and wastewater sludge handling and disposal. Sludge handling and disposal procedures are reviewed and evaluated by discussing methods, materials and equipment used today and in the past. Thus, the report provides an information base and suggestions for new approaches to the sludge treatment art for use by researchers, design engineers, and operators of treatment facilities.

The material is presented in the same sequence as solids processing steps used at treatment plants. The text begins with the grit chamber and ends with ultimate sludge disposal.

A major conclusion from the report is: additional support should be given to the research and development of better ways to treat the solid portion of wastewaters, after separation from the liquid.

Eight other major conclusions of the report are: (1) Standardized accounting and reporting procedures are needed. (2) Sludge handling and disposal should be integrated into the total wastewater treatment system. (3) Wastewater sludge disposal could be considered as a part of total solids-disposal system that includes refuse and other solid wastes. (4) Incineration is a promising ultimate disposal technique. (5) Mechanical dewatering systems are replacing more primitive dewatering systems. (6) There is a trend to ocean disposal of sludge by coastal or near-coastal cities. (7) Raw sludge handling is becoming more popular. (8) The cost of ultimate sludge disposal for most installations ranges from \$5 to \$55 per ton of dry solids.

# 1. INTRODUCTION

In January, 1930, the editors of the Sewage Works Journal quoted the following passage from Charles Rann Kennedy's -- "The Servant In The House:"

> "That's what I come 'ere to tak abaht -- my job.
> P'r'aps you'll think as it ain't tasty subjec, before
> a lot o'nice, clean, respectable people as never 'ad anythin'
> worse on their fingers than a bit o' lawn dirt, playin'
> crokey; but some one 'as to see to the drains, some one 'as
> to clear up the muck of the world; I'm the one, an I'm
> 'ere to tell you abaht it."

Probably since wastewater plants were first constructed, cleaning up "the muck of the world," or sludge handling and disposal, has been considered as the most troublesome phase of sewage and industrial waste treatment. Because more efficient wastewater treatment plants are constructed and operated to produce more difficult-to-handle sludges, this phase of water pollution control is becoming an increasingly difficult problem. The problem is complicated also by rising volumes of sludge from domestic and industrial sources coupled with reduced land availability and lessening public tolerance of air and water pollution. This situation has narrowed the choice of acceptable disposal practices in many locations.

Many people have made the statement that sludge handling and disposal is the most difficult part of wastewater treatment but it is well to remember that it is often the most costly. This is of particular consequence when considering that the total gallons of sludge produced is frequently less than one percent of the total gallons of wastewater collected and treated.

Sludge may be defined as: a semi-liquid waste having a total solids concentration of at least 2500 ppm. It flows, it can be pumped; and it exhibits hindered settling characteristics in gravity settling basins. Sludge handling and disposal includes: (1) collection of the sludge, (2) transportation of the sludge, (3) processing the sludge to convert it to a form suitable for disposal, and (4) final disposal of the sludge. It has been stated that final disposal is accomplished only when the material has been entirely removed from the treatment plant in a manner that is sanitary, permanent, and satisfactory to all parties concerned.

For this report, the above definition of sludge is expanded to include grit and screenings. These are discussed because they are an integral part of the total solids handling and disposal process at waste treatment plants.

Water plant sludge as well as wastewater sludge is discussed because it too is becoming increasingly difficult and costly to dispose of in a satisfactory manner.

Most of the discussions concerning various unit processes emphasize sewage sludge handling and disposal because the technical literature contains comparatively little information about industrial wastewater sludge. However, the unit processes and equipment are usually the same for both sludge types; thus, the information is generally applicable in all circumstances.

This study critically reviewed and evaluated water treatment and waste treatment sludge handling procedures. It discussed the methods, materials and equipment in use today as well as those that have been tried and abandoned in the past. The review of the art followed the sequence of solids processing established at waste treatment plants, starting with the grit chamber and ending with ultimate sludge disposal. A discussion of theory, important parameters, performance and cost data, degree of success and areas of possible improvements was included for most unit operations.

Information used in the report was collected from many literature references plus interviews with consulting engineers, equipment manufacturers, regulatory agency personnel and operators of water and waste treatment facilities.

The basic purpose in writing this report was to provide a comprehensive study of sludge handling and disposal to serve as a review of the known art for researchers investigating improvements in the art. It also includes some suggestions for new approaches to consider in the future. Design engineers, operators of water and waste treatment plants, and regulatory agency personnel will hopefully find the report to be a useful general reference on sludge treatment.

## 2. SUMMARY AND CONCLUSIONS

Preventing water pollution by removing solids from sewage and industrial waste is the primary purpose of waste treatment. The effluent, sludge and gases obtained as by-products of the treatment process must be disposed of efficiently, at a reasonable cost, and without risking public health and good will. By and large, researchers and design engineers have neglected sludge disposal in favor of the more glamorous problems associated with advanced waste treatment of the wastewater effluent. Likewise, the problem of gas has often been ignored.

The specific objectives of sludge handling and disposal are:

1. To decompose organic matter to a relatively stable material.
2. To reduce sludge volumes by removing liquids.
3. To destroy or control pathogens.
4. To use by-products of the process to minimize the overall cost of operation.

Which process is selected to accomplish the above objectives depends on the following:

1. Character of the sludge; raw, digested, or industrial.
2. Land availability.
3. Suitability of sludge for disposal by dilution.
4. Local possibilities for using sludge as a soil conditioner or fertilizer.
5. Climate.
6. Capital and operating costs.
7. Size and type of wastewater treatment plant.
8. Proximity of the plant to residential areas and local air pollution control regulations.

The objectives, and processes used to accomplish them, are given different emphasis depending on whether the sludge source is industrial or municipal. Important factors responsible for the difference in outlook are: (1) industrial sludge may be mostly inorganic, (2) industrial and municipal sludges can have vastly different handling characteristics, (3) industry has a greater interest in unconventional disposal methods, and (4) industry is more insistent about low costs.

Sludge must be considered a liability to any waste treatment plant; there is no known technique for making a profit on its collection and treatment. Often the case in any decision, the method of sludge handling and disposal selected is usually the one that is most economical yet acceptable to all parties concerned.

The following general observations can be made from a review of all sludge handling and disposal processes in use today:

1. Anaerobic digestion followed by sand bed dewatering is the most common method of handling sludge at sewage treatment plants. The obvious reasons for its popularity are simplicity and low cost. Few large cities dewater sludge on drying beds.

2. Lagooning is the most common method that industry uses to dispose of waste sludge.

3. For coastal cities, anaerobic digestion followed by pipeline transportation to the ocean or land reclamation areas is by far the cheapest method of sewage sludge disposal.

4. For many near-coastal cities with navigational access to the ocean, digestion followed by barging is the most economical method of sludge disposal.

5. Marketing dried waste sludge has been generally a failure. Heat drying of sewage sludge is, therefore, rarely given serious consideration by consulting engineers.

6. Sludge treatment presents many operational problems involving odors, inefficient solids capture, constant supervision and general lack of scientific controls.

7. Almost all of the methods of sludge handling and disposal now used were known in 1930(49).

Certain trends are noticeable in the field:

1. Mechanical dewatering of sludge is being adopted by increasing numbers of cities and industries due to increasing land and labor costs. This acceptance includes cities having populations formerly considered too small for mechanical dewatering techniques.
2. Sludge incineration is considered to be the process with the brightest future. Its popularity will continue to increase at a rapid rate as other disposal techniques become unacceptable. Incineration is being accepted at small as well as large installations.
3. Raw sludge incineration is replacing anaerobic digestion at medium and large size treatment plants.
4. Barging of digested sludge to the ocean is being considered and adopted by more and more cities near coastal areas.
5. The use of centrifuges in place of vacuum filters is growing.
6. The overseas popularity of composting sewage and industrial waste sludge is declining.
7. Land disposal of liquid digested sludge is increasingly popular at small sewage treatment plants.
8. Design engineers and plant operators are giving less consideration to sludge elutriation and heat drying sludge.
9. Competition is increasing among equipment and chemical suppliers. As a result, equipment design and chemical activity is being improved continuously. During the past four years, there has been a steady substitution of polymeric flocculants for inorganic types in sludge conditioning processes.
10. Sludge volumes are rising and becoming more difficult to dewater.

Despite changes and developments in sludge disposal procedures, insufficient attention has been paid to the problem. Sludge handling and disposal deserves more attention for many reasons. First, it is a costly operation. Often it represents 25 to 50 percent of the total capital and operating cost of a wastewater treatment plant. Second, it is the most annoying phase of waste treatment for the plant operator. The process presents him with many problems that he must solve with inadequate tools. Unfortunately, efficiency of sludge handling and disposal depends on the ingenuity of the plant operator. He has done a remarkable job, but the substitution of some science for the operator's art is long overdue. Finally, the problem is growing; as indicated by McCarty's estimate, the volume of waste sludge will increase 60 to 70 percent within the next 15 years (61).

Sludge handling and disposal should be an integral part of the total waste treatment process. The effectiveness of the waste treatment system and, therefore, the quality of the receiving water is influenced by the efficiency of sludge handling and disposal processes. Unless these are of the highest efficiency, filtrates, centrates, elutriates and particularly digester supernatant liquors overload these units with fine solids, upon return to clarification and biological treatment units; this lowers the overall plant treatment efficiency. This fact should be considered in plant designs.

A study indicated that only 4 to 9 percent of the nitrogen in raw sewage sludge is removed by the sludge digestion process(65). The remaining 91 to 96 percent is returned to the treatment plant as supernatant liquor and passes through, often unchanged, to the receiving water. Fertilization of receiving waters by nitrogen and phosphates is one of the major water pollution problems.

Air pollution may be caused by any number of sludge handling processes including incineration, heat drying, lagooning, sand bed dewatering, and raw sludge thickening. In this case, the waste treatment objective of maintaining good will is in jeopardy.

There is no doubt that new approaches to the problem of sludge disposal are needed. Suggestions for new approaches are discussed in detail at the end of each section in this report and in the final chapter. Additional research into the practical aspects of sludge treatment should be encouraged immediately.

## 3. SCREENING, DEGRITTING, AND SKIMMING

General - Grit and screenings are waste solids that must be disposed of at wastewater treatment plants along with skimmings and other solids. Fortunately their volume is very small so disposal is not as complicated as that for other solids collected in the treatment processes.

Screenings are materials in the raw wastewater that are caught on screens having openings usually 1/2 inch to 2 inches. The screens, placed at the head of the treatment plant, remove materials such as rags, sticks, and garbage. Grit can be described as small inorganic solids that are removed from the wastewater after screening. Examples of grit are sand, silt, gravel, ashes, and coffee grounds. Skimmings consist of all types of flotable material which rises in sedimentation tanks.

While small in volume, it is desirable to remove grit, screenings, and skimmings because these solids cause the following operational problems: (1) they plug, wear out, and break pumps and other mechanical equipment; (2) they occupy space needlessly in treatment units, particularly digesters; (3) they are difficult to remove from treatment units such as digesters and sedimentation basins; (4) they can clog pipes and solids dewatering equipment; and (5) they can produce odors and interfere with digestion.

Screenings Disposal - The quantity of screenings captured in a treatment plant is 0.5 to 6.0 cu. ft. per million gallons of sewage for screen openings of 1/2 to 2 inches and 5.0 to 3.0 cu. ft. for openings of 3/32 to 3/4 inches(1). Screenings have a moisture content of about 85 to 95 percent and an organic content of 50 to 80 percent(8). A sanitary means of disposal is required due to the high organic content. Therefore, these materials are usually buried. Sometimes they are incinerated or ground by hammermill-type shredders into small particles and added to sewage for later removal in sedimentation basins.

Burial after draining for about one day is the most common means of screenings disposal. The solids are placed in a hole or trench and covered with at least 6 inches of dirt. Lime and odor-masking chemicals are sometimes used to prevent nuisance problems such as odor development and insect breeding.

Incineration is possible in a separate unit, in a skimmings incinerator, a refuse incinerator, or a dewatered sludge incinerator. The screenings moisture content before incineration should be reduced to about 60 to 65 percent by drainage, pressing, or dewatering in a centrifuge. One pound of screened solids has a Btu value of 1400 to 3500(1).

Grit Disposal - Grit is removed at almost all sewage treatment plants even though the wastewater collection system is separated so theoretically street washings will not be a part of the wastes to be treated.

There are two approaches to grit removal: one advocates grit collection units at the head of the treatment plant; the second advocates the use of hydrocyclones to remove grit from the settled solids in the primary sedimentation basins. At the present time, hydrocyclones are installed in only a few waste treatment plants, primarily because they are relatively new, but there is considerable data proving their great efficiency.

Heavy inert particles or grit are selectively deposited in units, installed at the head of treatment plants, by velocity control in simple gravity settling structures or by air flotation-classification of the inerts and lighter organics in aeration tanks. Aerated grit chambers have the disadvantage of being a source of odors, so they are not recommended when septic wastewater is expected unless the unit is completely covered to capture gases and thereby reduce odors.

Generally, grit collection units are designed to remove particles having a specific gravity of 2.65 and diameters down to 0.2 mm. The quantity of grit collected normally varies from 1 to 12 cu. ft. per million gallons with an average of 4(7). Specific quantities removed depend on many parameters including topography in the wastewater collection area, the surface cover, size of sewers and whether they are separate or combined, the intensity of rain storms, and the design of the grit removal system. The moisture content of grit varies from 14 to 34 percent. Grit is often washed after collection to reduce the organic concentration which may be as much as 50 percent of the total solids.

The nature and quantity of the grit influences the method of ultimate disposal. Because there is often a high concentration of organics, burial is the most common disposal technique. Burial reduces the chance of developing odor, insect, and rodent problems. If solids separation is very efficient and if less than 15 percent volatile solids are included in the grit, it can be disposed of as fill without nuisance. Well-washed grit has been used on sludge drying beds, as a cover for screenings, and as a surfacing material for walks and roadways. A few sewage treatment plants have incinerated grit along with dewatered sludge. Being largely inorganic, most of the grit solids are ultimately discharged with the incinerator ash.

Skimmings Disposal - The volume of scum or skimmings collected from sedimentation basins or separate skimming tank normally varies from 0.1 to 7 cu. ft. per million gallons of sewage. Wide variations are possible due to industrial discharges to the sewerage system. Skimmings normally have a moisture content of 60 to 90 percent and a volatile solids concentration of 90 to 95 percent. Because skimmings are collected as floating material, they include high concentrations of grease and fibrous trash. The heat value can vary from 8,000 to 18,000 Btu per pound.

Skimmings are usually disposed of in one of four ways: (1) buried; (2) pumped to digesters; (3) dewatered by mechanical equipment; or (4) incinerated. Burial is simple but requires immediate covering and concern for nuisance problems. Disposal to digesters is very common, particularly with completely mixed units. Without thorough digester mixing, skimmings may form a scum layer which leads to operational problems. Dewatering requires careful control to avoid media plugging. Vacuum filter dewatering normally requires prior mixing with other more easily drained materials. Skimmings, however, could be added to a vacuum filter after a sludge precoat has been formed.

Burning skimmings in incinerators is becoming more popular as the volume of material increases with the increased use of garbage grinders. Separate incineration of skimmings at the source (skimming tank or sedimentation basin) is recommended by some people because it eliminates operational problems associated with pumping grease to a distant incinerator. However, incineration of this highly volatile and high Btu value material can be a problem due to the development of high temperatures. Most conventional incinerators are not constructed to withstand the very high temperatures (in excess of 2,000°F) that can result from burning skimmings without other lower Btu value solids. In addition to incinerator damage from high temperatures, flashing and odors are two problems that may develop from the burning of skimmings, if proper design and operational procedures are not adopted. Temperatures can be reduced with water sprays. Flashing can be minimized in multiple hearth furnaces by a parallel flow of skimmings and hot gases.

The most common incineration technique is to burn the skimmings in the same furnace used for burning vacuum filter or centrifuge cake solids. Detroit, for example, has for years successfully burned grit and skimmings in a multiple hearth furnace used basically for incinerating filter cake solids(15). Before incineration, skimmings should be settled, the liquid decanted, and the solids ground to a small size.

A number of investigators have considered grease recovery from sewage treatment plant skimmings. This is a popular money saving scheme used in the wool-scouring and food processing industry. However, recovery of grease is not practical in the sewage treatment business because the volume is small and the grease is too contaminated with other materials. Purifying the grease would be too expensive and FDA approval is doubtful. Further comments are included in the By-Product Recovery chapter of this report.

Summary - The volume of screenings, grit, and skimmings collected at waste treatment plants is fairly small, but proper disposal is important because they are the most objectionable materials processed. Problems involving odors, insects, rodents, and unsightliness can develop if these solids are not correctly handled. Burial, grinding with discharge to raw wastewater, and digestion with adequate mixing have been satisfactory methods of disposal. In the future, incineration will be more popular. However, incinerator design should be improved if skimmings and screenings are to be burned without the addition of dewatered sludge.

## 4. CLARIFICATION

Introduction - The water and wastewater solids, requiring treatment and disposal first must be collected in some kind of basin or screening mechanism. At sewage treatment plants, most of the solids are separated in primary sedimentation basins from the liquid transporting them. In addition to raw waste, disintegrated screenings and secondary sludges from the biological stage of the treatment process may be settled in primary sedimentation basins. The secondary or biological sludges may also be captured in final or secondary sedimentation tanks. In some cases where the sewage is weak and the solids are primarily organic, sedimentation before the activated sludge process has been eliminated in the design of treatment plants. Flotation rather than sedimentation is often prescribed for removing certain industrial wastewater solids, but it is rarely used for clarifying raw sewage.

This section discusses the theory and operation of clarification units in regards to the production of sludge most susceptible to dewatering and ultimate disposal.

### A. Sedimentation

General - The design and operation of sedimentation basins have emphasized B.O.D. and suspended solids removal rather than the production of the thickest and freshest sludge possible. Sludge thickening is usually considered to be the "second function" of settling tanks(97). Most investigators agree it is desirable to produce the freshest and most concentrated sludge possible for the following reasons: (1) it saves pumping and digester capacity, (2) it reduces the heat requirement for digesters, and (3) it saves chemicals and operating time when dewatering solids. Since securing the highest suspended solids removal efficiency is not necessarily incompatible with securing the thickest underflow solids, more attention should be given to the sludge characteristics, particularly at secondary treatment plants.

There are two schools of thought recommending different ways of achieving fresh and concentrated sludge. One advocates the Densludge process. Its proponents claim that the use of sedimentation basins for sludge thickening as well as for wastewater clarification sacrifices the basin efficiency for B.O.D. removal. The Densludge system involves the continuous pumping of low volumes of a dilute relatively fresh sludge from sedimentation basins to separate thickening tanks. Better efficiencies in primary sedimentation tanks are said to be possible when the sludge is pumped continuously at a low rate. This is because of the minimized changes in hydraulic flow and the elimination of sludge storage. Also eliminated is the accompanying possibility of solids escaping and septic conditions developing. Use of a separate thickener allows better control of the sludge; its operation has little effect on the clarification step. The Densludge process is discussed in greater detail in the chapter on Thickening in this report.

Most wastewater treatment plants are designed in accordance with the second school of thought, which holds that thickening as well as clarification should be attempted in sedimentation basins. As stated above, the usual basin design depends on optimizing the removal of B.O.D. and suspended solids from the wastewater. Designs are available however, that attempt to produce above average sludge thickening by including special equipment. One manufacturer accomplishes this by placing a large circular sludge hopper, one-third to one-half the diameter of the circular sedimentation tank, at the bottom of the tank. Theoretically, clarification occurs in the upper part of the tank and sludge thickening in the bottom. The hopper is provided with pickets for slow agitation of the sludge and piping for adding well aerated plant effluent or chlorine to the sludge blanket to prevent septicity. Another design uses a helix-screw mechanism in the sludge hopper of rectangular sedimentation basins. This device provides a kneading and squeezing action that collects and compacts the sludge. Both of the sedimentation tank modifications thicken the sludge to a greater degree than is possible with conventional basins. As expected, they make the tanks more expensive to construct.

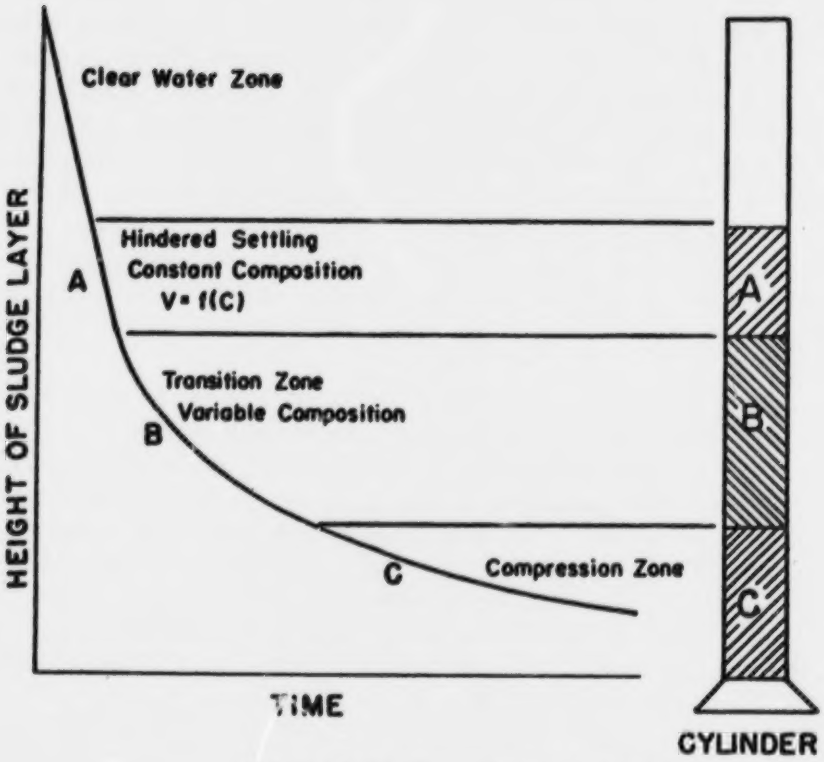
Theory and Design - Sedimentation is defined as: the removal of suspended particles heavier than water by gravitational settling(7). Many of the recommended parameters for efficient suspended solids settling will also benefit sludge thickening. These parameters include the basin depth and shape, sludge detention period, type of baffling utilized, and operating conditions. Consulting engineers and equipment manufacturers generally agree that the design standards recommended in the "10 States' Standards" are valid for sewage solids removal in primary and secondary clarifiers. Industrial wastewater clarification, because of the great variations in the solids characteristics, requires laboratory or pilot plant evaluations to determine the best hydraulic and solids loading parameters.

Many people, including Camp, Hazen, Cummings, and Kynch, have discussed methods and theory of designing continuous flow clarification units. (Fill-and-draw units are not discussed in this report because they are not common, particularly in sewage treatment.) Mancini reviewed the procedures for clarifier design. He concluded that batch settling tests can be used in designing clarifiers used to capture solids having hindered settling characteristics (including many industrial wastes) if the test conditions were related to the hydraulic performance of the particular full-scale unit under consideration(92). The batch settling test develops a settling curve that can be analyzed to determine the surface area required for clarification and the surface area required to concentrate the settled solids to a particular concentration. These tests define the settling characteristics which are affected by properties of the solids such as particle size, distribution, density, concentration and agglomeration(92).

Sedimentation is generally described as incorporating three steps: clarification, zone settling, and compression(7). This report is most concerned about the compression of solids after they pass through the clarification and settling zones. When the solids first reach the bottom of the sedimentation tank, they form a blanket having a high percentage of void spaces. However, in time and with additional settling of solid particles, the blanket becomes compacted due to the hydrostatic pressure of its own weight. During compression, water is squeezed from the compacting sludge mass. In effect, therefore, compression is the opposite of the preceding two steps inasmuch as a liquid is being removed from solids rather than solids from a liquid. Figure 4.I shows the different settling zones for biological sludges.

Factors that are thought to influence the concentration of the settled sludge in sedimentation basins include: (1) settleable solids characteristics - their density, shape, flocculant structure, viscosity, percentage of volatiles, and electrostatic charge; (2) the solids concentration in the original suspension; (3) the depth and surface area of the sludge blanket; (4) the sludge detention time, and (5) structural modifications of the sludge blanket by pressure, vibrations, and mechanical action(97). The first two factors are independent of the design of the sedimentation tank, but the next three are dependent upon its shape and other design features.

Figure 4.I


Clear Water Zone
HEIGHT OF SLUDGE LAYER
Hindered Settling
Constant Composition
V= f(C)
A
Transition Zone
Variable Composition
B
C
Compression Zone
TIME
A
B
C
CYLINDER

Schematic representation of settling zones.

(Reprinted by permission JWPCF, Vol. 29, No. 10, p. 115, Oct. 1957)

Many investigators agree that for a given detention time, a shallow compression zone will produce a greater underflow concentration than a deep one. As the depth is increased, the detention time must be increased to maintain the same solids concentration. With long detention periods there is the danger that organic sludges will become septic, causing odors and bulking, which in turn reduce the solids concentration. The decrease in compaction rate which accompanies increased sludge depth occurs because the displaced water has to pass upward through diminishing void spaces against increasing resistance to liquid flow. Water displacement can usually be enhanced by the hydraulic movement of the sludge blanket and by the action of the sludge collection mechanism breaking up the arched settled sludge. The degree of improvement from gentle agitation of the sludge blanket depends on the type of solids being settled.

Sludge collection hopper designs can have a significant effect on the underflow solids concentration. Inadequate hopper capacity can result in thin sludge because the operator is forced to withdraw sludge frequently to prevent it from accumulating outside the hoppers and becoming septic. Steeply sloped hopper sides (2:1) will aid in sludge concentration because sludge arching will be reduced. Sludge withdrawal pipes should be at least 8 inches in diameter and have a minimum of obstructing supports. These factors will decrease the incidence of clogged hoppers and arching sludge. A sludge depth of at least 18 inches in the hopper is recommended.

Settled sludge compaction is influenced by the following sedimentation basin currents: (1) eddy currents created by the inertia of influent and effluent flows, (2) wind-induced currents, and (3) density currents caused by wastewater temperature differences including that between the sludge blanket and the clarified overhead water(7). These currents and secondary currents established by their action can cause bottom scour of deposited sludge. Solids compaction will be reduced due to resuspension. The overall plant treatment efficiency may be reduced by the subsequent carryover of sludge to the weirs. The sedimentation basin inlet and outlet must be adequately designed to minimize the creation of currents. Effluent weirs should be adequate in length, and inlets should distribute the wastewater broadly over the entire cross-sectional area of the tank with minimum inlet velocities (96). Baffling the area in front of the inlet openings will help to reduce velocities and to distribute the flow broadly. Camp thought sedimentation tanks should only be deep enough to prevent scour and should be long and narrow to minimize the effects of various currents(97). Others may disagree but in any case, settling tanks should be able to accomplish a reasonable degree of sludge thickening as well as to separate settleable and floatable solids from liquids.

Operations - The operation of sedimentation basins is obviously closely related to the operation of other treatment plant processes. To facilitate subsequent sludge handling steps, it is usually desirable to deliver a thick, fresh sludge from the sedimentation basins. However, because the production of a thick sludge may require a long detention time, this goal may not always be compatible with the goal of achieving a fresh sludge. Some compromise in the goals may, therefore, be required. Good sedimentation tank operation starts with: (1) equalizing the flow between parallel tanks, (2) preventing density currents by using baffles and adjusting effluent weirs to give a uniform distribution, and (3) setting the wet well pumping controls to minimize surging in the basins(8).

Sludge collection and withdrawal parameters to be considered are: (1) depth of the sludge blanket, (2) operation of sludge collection mechanisms, (3) sludge pumping schedule, and (4) operation and maintenance of sludge pumps(8). Most settling tanks are operated with blanket depths between 2 and 6 feet deep. This level seems to give a reasonable sludge concentration without storing the sludge so long that extreme anaerobic conditions develop. Many operators of waste treatment plants successfully use the blanket depth as a measure of solids concentration as if the two were directly proportional. Sludge withdrawal is then controlled by the blanket depth. Compaction of settled sludge is usually thought to be enhanced by agitation, particularly for hydrous colloidal precipitates, but some people consider the degree of agitation introduced by the solids collection mechanism to be insignificant. To prevent resuspension of the sludge, the collection mechanism should be operated at 2 feet per minute or less. It normally is in operation when sludge is being pumped in order to prevent liquid from being "pulled through" the sludge blanket. Camp and others believe the sludge should be collected and moved in the same direction as the flow through the basin for maximum effectiveness(90).

Sludge withdrawal techniques have an important effect on concentration and freshness; prompt removal of heavy sludge is the goal. Sludge is usually removed by pumping or hydrostatic pressure. Biological sludges are sometimes removed by suction devices near their point of deposition if freshness is important. Industry and small sewage treatment plants often use the hydrostatic pressure method of disposal even though it has the disadvantage of displacing significant quantities of water with the sludge.

The question, "What is the best type of pump for sludge?" will produce answers indicating that almost any kind is suitable to someone.

Obviously, a pump that doesn't clog readily is desirable. Variable speed pumps that can deliver a small volume of sludge may be desirable.

Pumping sludge is the most common withdrawal technique and the particular schedule used determines the solids concentration and freshness. In general, the most successful operations have adopted a schedule having frequent but short pumping periods at low rates such as 25 gpm. The schedules normally are determined by experience because of the varying solids load received at the treatment plant. Once a pattern is established, the pumping schedule is programmed on a time clock or set manually. At small waste treatment plants sludge is pumped about one to three times each day and at large plants, hourly.

The sludge "quality" is usually controlled by visual means through sight glasses or with sampling valves located between the sludge pump and the digester or other points of disposal. Other indications of sludge thickness are obtained by reading pump discharge pressures, checking the torque developed on the settling tank scraper mechanism, noting the sludge blanket depth, or by radioactive density (or mass) analyzer readings.

Not all radioactive density meter installations have been successful but the one at the Los Angeles County Sanitation District has been given credit for contributing to smooth treatment plant operations. Garrison describes this completely automated sludge pumping control system as having two basic components: non-clog sludge pumps and radioactive density meters(105). At the District's Main Treatment Plant the average solids concentration has been increased from 3.5 percent before automation to 6 percent after automation. The increased consistency in digester performance obtained after automation has been attributed in part to the increase in solids concentration. The density meter is preset at 6 percent and electrical control equipment permits sludge pumping only when the concentration is near that figure. One meter can control sludge pumping from six sedimentation tanks(18). Visual observations were unsuccessful because of human error and because changes in sludge were noticed too late. The use of timers to control pumping was unsatisfactory because the rate of sludge accumulation was not uniform. Current-sensitive relays on motors to measure the change of power required at different sludge concentrations also produced erratic results in comparison with density meter control(18).

Keefer evaluated radioactive density meters at Baltimore and found them to be very accurate over a range of sludges from 0.1 to 6.6

percent total solids(95). Gerson Chanin reported that the concentration of primary sludge significantly increased in the East Bay Municipal Utility District plant after substituting the density meter for visual control of sludge pumping. He reported that calibration of the meter by digester supernatant has maintained a uniform operation. This fact is probably significant when reviewing the performance of radioactive density meters. Frequent maintenance and calibration are probably necessary for a successful system.

Any technique that will insure the pumping of thick sludge is desirable because subsequent sludge handling costs and problems are reduced. A minimum amount of water is pumped; digester operations are improved because less heat and space is required; less supernatant liquor is produced; and sludge dewatering process costs are reduced. The radioactive meter may not, however, be the ultimate control device; perhaps ultrasonics or some other technique will prove to be even more successful.

Performance - The volume, concentration and general characteristics of the sludge produced by sedimentation will be affected by a number of factors including the following(70):

1. Characteristics of the raw wastewater from which the sludge is derived.
2. The type of secondary treatment given the wastewater and whether secondary sludges are handled separately or returned for resettling with the primary sludge.
3. The design and operation of the sedimentation tanks.
4. Whether chemical or mechanical aids to settling are used.

Characteristics of sewage and industrial wastewater vary tremendously, so it is natural to expect the sludges to vary likewise. After the wastewater is in the sewer, there is not much that can be done about changing the basic nature of the sludge. Biological processes produce large volumes of dilute flocculent sludges that are difficult to dewater. In many cases trickling filter humus and waste-activated sludge are returned to the head of the treatment plant where they are resettled with the primary sludge. The uniform mixture of the two types of sludge may facilitate ultimate sludge dewatering and final disposal. Fair and Geyer report the expected sludge concentrations for separate and mixed (primary and secondary) sludges as described in Table 4.1(7).

Table 4.1

| Type | Solids Conc. |
|---|---|
| Raw Sludge | |
| Plain sedimentation | 2.5 - 5% |
| Trickling filter | 5 - 10% |
| Trickling filter, mixed | 3 - 6% |
| Activated | 0.5 - 1% |
| Activated, thickened | 1 - 2% |
| Activated, mixed | 4 - 5% |
| Digested Sludge | |
| Plain sedimentation | 10 - 15% |
| Trickling filter | 10% |
| Activated | 2 - 3% |
| Activated, mixed | 6 - 8% |

With biological sludges in particular, the possible underflow concentration that can be achieved is limited. The sludge in the settling basin will consume the available oxygen and deteriorate into an anaerobic condition if the detention period is too long. This could result in gasification and floating of the sludge to the surface of the tank.

Pre-aeration of sewage prior to primary sedimentation is a fairly common technique. It offers the advantages of separating grease and grit from the other sewage solids; it degasifies the sewage; it freshens the sludge and improves its settle-ability and degree of compaction. Pre-aeration is particularly useful if the raw wastewater is septic(4, 81). Mechanical flocculation also may improve the settle-ability and subsequent compaction of sludge by encouraging particle agglomeration.

Chemicals have been applied to raw wastewaters for many years with varying degrees of success. Alum, lime, and iron salts have been used to achieve intermediate levels of treatment but the effect on sludge handling has been to complicate the process. Large volumes of sludge are produced due to the additional solids removed from the wastewater plus the large quantities of added chemicals. Lime also produces an unfavorable pH and alkalinity for sludge digestion.

Chlorine treatment of wastewater, including mixed liquor solids, has improved subsequent sludge handling procedures by reducing septicity, allowing better grease separation, and reducing the bound water and sludge volume index (SVI) in bulky activated sludge. A more concentrated settled sludge and improved digester operation are two resultant advantages. Use of 10 ppm chlorine reduced the SVI from 177 to 120 and the bound water in the sludge by 47 percent(87). Copper sulfate has been used in place of chlorine at a dosage of 5 to 8 ppm(93).

Polyelectrolytes are being successfully employed in applications that produce thicker underflow solids concentrations with subsequent improvements in dewatering and digester operations. Crowe and Johnson reported on the use of a low dose of anionic polymer at Battle Creek, Michigan, to capture additional suspended solids in the primary clarifiers(102). The use of the chemical also increased the concentration of raw sewage solids from 4.3 to 8.0 percent, which in turn increased the effective capacity of the sludge holding tanks and digesters. The thicker sludge permitted a smoother dewatering operation at reduced chemical costs and vacuum filter operating time.

The results provide an excellent illustration of the operational improvements that can be obtained through increased sludge solids concentrations. Because the cost of treating secondary sludge is much greater than that for primary sludge, it is an advantage to increase also the ratio of primary to secondary sludge. A significant increase is possible with chemical treatment of the raw wastewater.

## B. Flotation

General - Flotation-clarification processes are in use at numerous industrial waste treatment plants and a lesser number of sewage treatment plants. Three methods of flotation, using rising air bubbles to increase the buoyancy of solid particles, are most commonly used: (1) dispersed air flotation where bubbles are generated by introducing air through a revolving impeller or porous media, (2) dissolved air-pressure flotation where air is put in solution under elevated pressures and later released at atmospheric pressure, and (3) dissolved air-vacuum flotation which applies a vacuum to wastewater aerated at atmospheric pressure(6).

As expected, sludge "skimmed" from raw wastewater flotation units contains large quantities of grease, oils, and other low-specific-gravity materials. Little data has been reported describing the performance of these units when used for dilute wastewater clarification, but it can be assumed that the floatable material collected would be difficult to handle. The solids concentration of the sludge (or float) would be affected to an unknown degree by the air-to-solids ratio used by the detention time in a floated state, and whether or not chemicals are added. In the food industry the floated material is often collected and sold as a by-product of waste treatment.

A detailed discussion of dissolved air flotation as it applies to separate sludge thickening is presented in the Thickening chapter of this report.

## 5. SLUDGE THICKENING

Introduction - Thickening or concentration can be defined as the process of removing water from sludge after its initial separation from water and wastewater. The basic objective of thickening is to reduce the volume of liquid sludge to be handled in subsequent sludge disposal processes (65).

Sludge thickening provides the following advantages:

1. Improves digester operation and costs because space is conserved, the heating requirement is decreased, the detention period of existing units is increased, less supernatant liquor is produced, a higher solids loading to the digester per cubic foot is possible, and the microorganisms active in the digestion process are more efficient.
2. Reduces the sludge volume and, therefore, the costs of sludge pumping and ultimate disposal to the ocean or land.
3. Reduces the cost of chemical conditioning prior to sludge dewatering because of increased solids concentrations.
4. Eliminates water where it usually is the easiest to do so, ahead of digestion and dewatering.
5. Smooths-out fluctuations in sludge quantity and quality.
6. Generally reduces treatment costs due to savings, such as in the physical plant size, labor, and power.

Thickening used to be considered an art, but today there are proven techniques that elevate the process to an engineering science if not an exact science.

The degree of concentration that can be expected from various thickening processes depends on several variables. Certainly the method of wastewater treatment is very important as is the initial composition of the raw wastes. The difference between biological flocs and raw primary sewage provides a good example of the variations that can result from different treatment methods -- biological flocs are bulky and concentrate to a lesser extent than raw primary sludge. The initial concentration of the sludge to be thickened, the density of the particles, their size and shape, the temperature and age of the sludge, and the ratio of organics to inorganics are also important factors in the final sludge concentration produced. Thickening in separate units can produce a more concentrated sludge than thickening in the initial wastewater clarification units.

Sludge concentration becomes the primary objective while overhead clarity assumes a secondary role; this situation is the reverse of sedimentation-clarification.

The simplest method of thickening is gravity settling without the use of mechanical or chemical aids. In the search for methods producing higher concentrations than is possible with simple gravity settling, other techniques have been evaluated and adopted. These include: (1) biological and dissolved air flotation, (2) centrifugation, and (3) chemical conditioning.

## A. Gravity

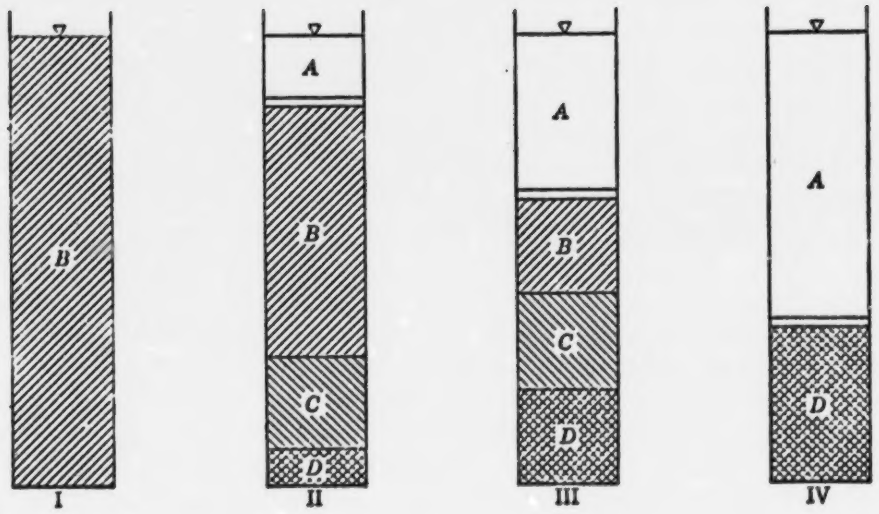
General - Thickening by gravity is the most common concentration process in use at wastewater treatment plants. It is simple and inexpensive, but it does not produce as highly concentrated sludges as other thickening processes. Gravity thickening is essentially a sedimentation process similar to that which occurs in all settling tanks. But, in comparison with the initial waste clarification stage the thickening action is relatively slow(65). The operation of gravity thickening tanks has generally been satisfactory but improvements in the degree of solids concentration are always desirable.

Theory, Parameters, and Design - Gravity thickening usually exhibits the "hindered" settling phenomenon due to the relatively concentrated nature of the sewage and industrial wastewater solids. According to Mancini this hindered settling phenomenon is influenced by the particle size distribution, density, concentration and agglomeration as well as the hydraulic conditions in the settling basins(92). Most investigators recognize four basic zones in a gravity thickening system: (1) a clarification zone at the top containing the relatively clear supernatant liquid, (2) a settling zone characterized by a constant rate of solids settling, (3) a compression zone characterized by a decreasing solids-settling rate, and (4) a compaction zone where the settling rate is very low(6, 92). Figure 5.I illustrates these zones and labels them respectively as A, B, C, and D(6).

In the settling zone the particles are settling under hindered conditions but their concentration ramains the same. The settling rate in this zone can be used to determine the area required for wastewater clarification. In the compression zone the solids concentration increases as the entrained water is forced upward through void spaces. The solids settling rate decreases as the resistance to relative motion

Figure 5.I

Thickening Zones



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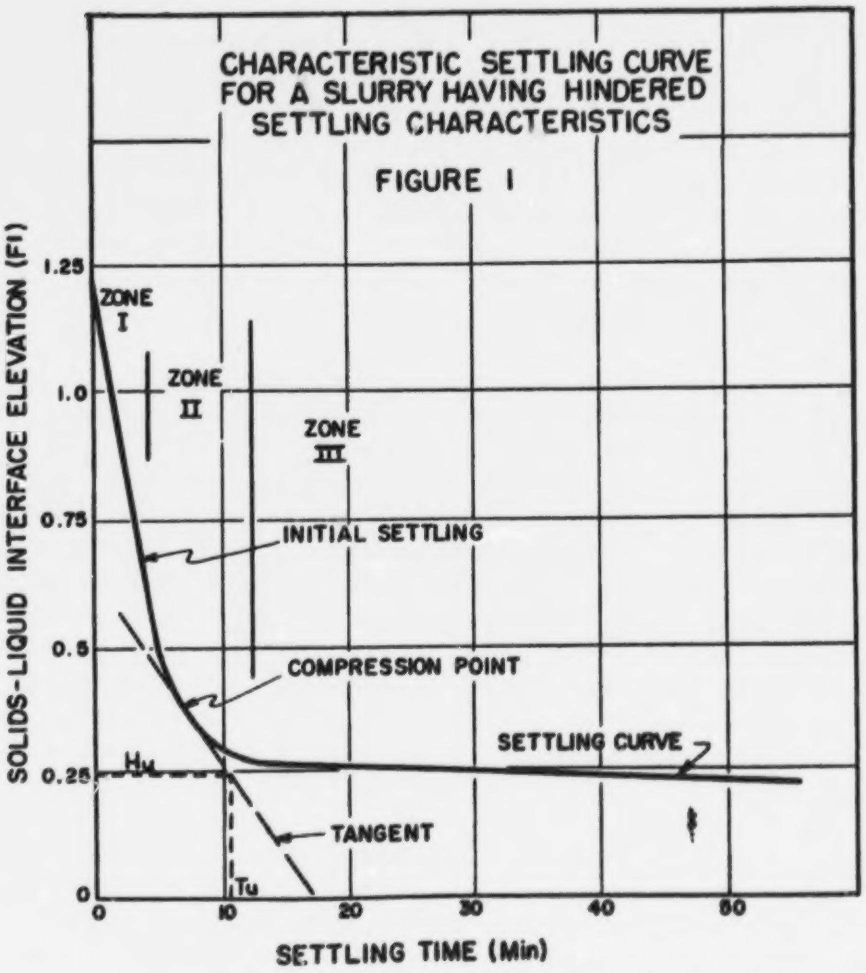
between the solid and liquid phase increases (92). An analysis of a plot of this zone can also be used to obtain thickener design parameters. The compaction zone is the last zone; it is defined as an area supported by the solids below them(6).

Numerous studies by Kynch, Talmadge, Fitch and others have revealed that continuous thickening units for suspensions with hindered settling characteristics can be designed on the basis of data collected during batch settling tests(99, 100, 112). A solid-liquid interface settling curve developed from laboratory tests can be used to determine the surface area required for clarification and the surface area required to thicken the sludge to a particular solids concentration. Mancini believes, however, that the batch test has only a limited usefulness and pilot plant studies should, therefore, be considered in order to develop a more reliable design criteria(92). A typical curve and how it can be used to design thickening units has been described by Mancini(92). Figure 5.II shows one of his typical curves. As reported by some engineers, a comparison of actual operating results with the batch settling lab tests has often indicated that the plant-scale unit performs better than anticipated(112).

The degree to which waste sludges can be thickened depends on many factors; among the most important are the type of sludge being thickened and its volatile solids concentration. Figure 5.III by Budd, shows the relationship between the underflow solids concentration and the percentage of volatile solids for primary sludge and a mixture of primary plus biofilter sludge(23). Bulky biological sludge, particularly that from the activated sludge process, will not concentrate to the same degree as raw primary sludge. The degree of biological treatment and the ratio of primary to secondary (biological) sludge will affect the ultimate solids concentration obtained by thickening. It is obvious from the data shown in Figure 5.III that higher solids concentrations are attained with a decrease in the sludge volatile content.

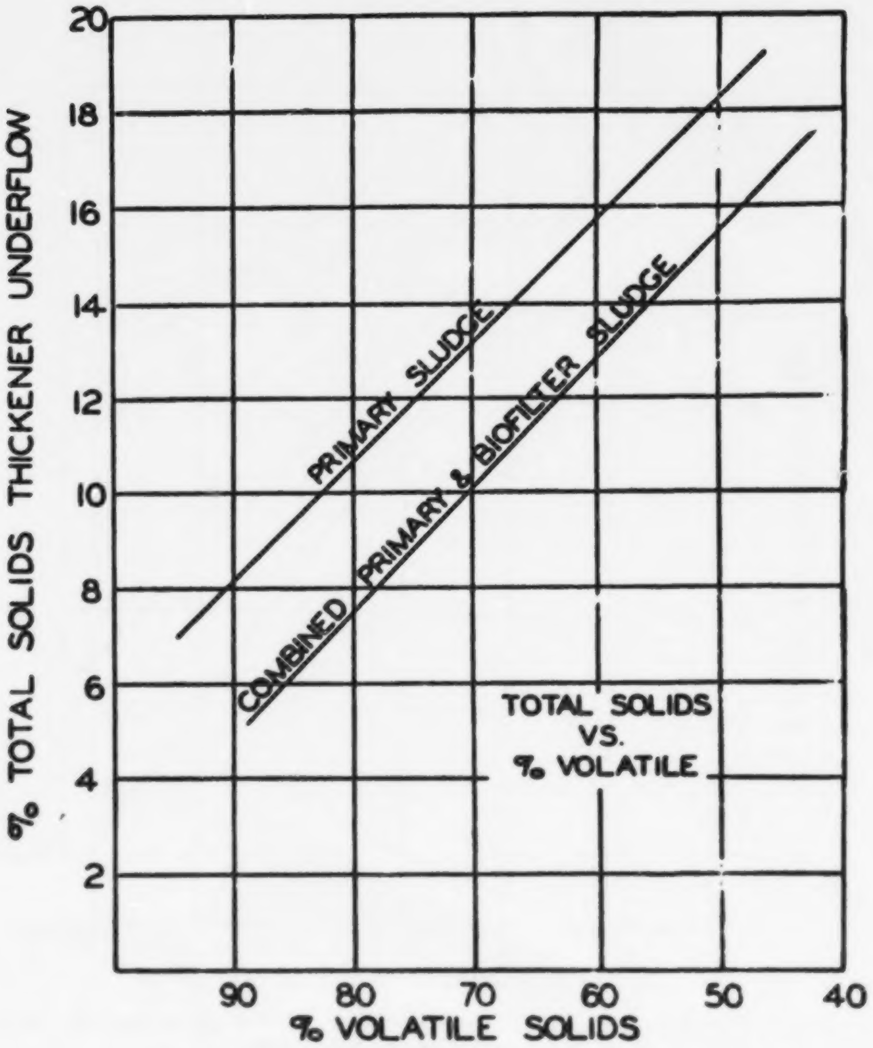
Rudolfs and Logan investigated the importance of initial solids concentration and temperature on sludge thickening(34). As shown in Figure 5.IV, the percentage increase in settled solids concentration is much greater with low initial feed solids concentrations than with a high concentration thickener feed. The importance of temperature is also significant, particularly with "aged" sludge. Compaction is greatest at 37°C, regardless of the initial feed solids concentration; higher and lower temperatures resulted in less compaction.

Figure 5.II



(Reprinted by permission Schools of Engineering, Purdue University)

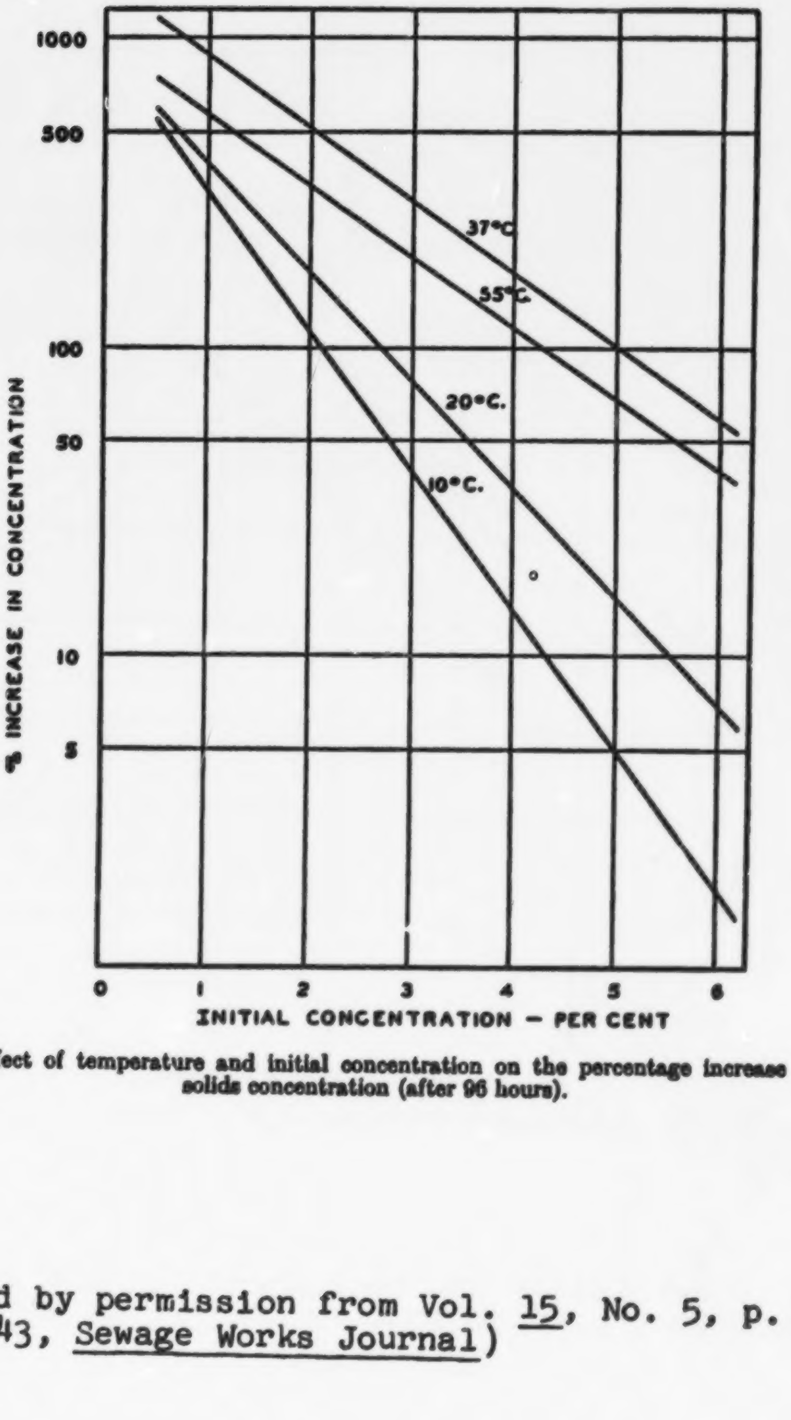
Figure 5.III



Relationship of total solids to percent volatile solids.

(Reprinted by permission Southern Municipal and Industrial Waste Conference, p. 166, 1959)

Figure 5.IV



Effect of temperature and initial concentration on the percentage increase in fresh solids concentration (after 96 hours).

(Reprinted by permission from Vol. 15, No. 5, p. 898, Sept. 1943, Sewage Works Journal)

In general, laboratory pilot-plant and full-scale investigations of the importance of initial solids concentration have determined that optimum results are achieved when a feed solids concentration is between 0.5 and 1.0 percent(117, 118). Within this range the settling rate is rapid, and the sludge compaction and overhead clarity are optimized.

New York City achieves good underflow solids concentrations by thickening mixtures of dilute raw primary and activated sludge as part of a process called the Denssludge system. This system depends on a dilute sludge mixture which is normally achieved by pumping underflow from both primary and secondary clarifiers continuously at a ratio of about 8 parts secondary sludge to 1 part primary. The solids concentration of the feed solids mixture at New York is normally a little less than one percent(114). New York recently reported further increases in the average sludge compaction by the technique of adding digested sludge to the raw sludge thickener feed. Without dilution, the solid-liquid separation process is much slower due to interference between the particles.

Most investigators believe the depth of the sludge blanket in a thickener is an important parameter as regards the ultimate solids concentration. However, contrary to what might be expected, it is generally agreed that underflow solids concentrations are independent of sludge blanket depths greater than 3 feet (117, 118). Comings determined for a constant detention that the underflow solids concentration decreased as the depth of the compression zone increased(99). At depths greater than 3 feet, there is apparently a significant increase in the resistance to the flow of water from the sludge blanket. Also, as the sludge accumulates in the deeper blankets it often becomes septic, producing entrained gas and a bulky sludge which doesn't compact well.

Sludge blanket depth and detention time are naturally closely interrelated. Most observers agree that increased detention of the solids in the sludge blanket results in increased solids concentration, up to a point. For maximum compaction, 24 hours has been suggested as the time required(118). Comings reports the underflow solids concentration increases as the detention time increases in a compression zone of constant depth(99). A compromise must, therefore, be made between detention time and the sludge blanket depth parameter described in the preceding paragraph. It has been suggested that a specific sludge concentration is attained in the shortest time by operating with a shallow compression zone depth(99). Greater depths require greater detention times, but where organic sludges are involved a greater septicity will occur.

Gentle agitation of the sludge blanket is generally thought to facilitate compaction, but the degree of compaction depends on the type of sludge. Hydrous colloidal precipitates and certain metallurgical pulps particularly benefit from agitation(101). It has been claimed that the efficiency of a thickening tank can be improved from 15 to 20 percent by attaching vertical steel members or "pickets" to the sludge collection mechanisms(70). These "pickets" move through the sludge blanket and create passages for entrained water and gas to reach the surface, as well as aid particle agglomeration. Mancini presented data demonstrating that gentle mixing of activated sludge greatly increased the settling rate of the sludge. Schroepfer and Ziemke also reported a dramatic increase in the solids concentration of anaerobic sludge by the use of pickets (wickets)(36). Laboratory and pilot-plant tests will indicate to what degree agitation aids thickening.

Chemicals and inert weighting agents can influence the degree of sludge thickening and its freshness. Rudolfs investigated many different additives to many different sewage sludges(33). He observed that alum and ferric salts did not significantly increase sludge concentrations after 24 hours compaction. Sulfuric acid improved the compaction of sludge, but the required dose (600 - 1000 ppm) is economically impractical. Lime dosages of 250 to 500 ppm increased significantly sludge compaction.

Rudolfs also added iron oxides, diatomaceous earth, and fly ash to sludge to promote compaction, but the effects were insignificant at reasonable dosages(33).

Chlorine can be used to prevent sludge septicity and gasification which interferes with optimum solids concentration of organic materials. Decomposition of unstable sludges during thickening process can produce gas which adheres to the solid particles, changes their density, and often buoys them to the liquid surface(11). A chlorine residual of 0.5 to 1.0 ppm in the thickening tank overhead prevents this problem. Overdosing must be avoided because excessive chlorine may disperse biological sludges(5).

The successful use of organic polyelectrolytes as aids to sludge compaction has been demonstrated by a number of investigators. Anionic, cationic, and nonionic polymers are known primarily to increase the sludge settling rates, the overhead clarity, and the allowable tank loadings, but often they also increase the settled solids concentration. Higher dosages produce higher degrees of compaction. Returning filtrate containing some residual polymer or inorganic flocculent from the vacuum filter operation to the thickening tank may produce some beneficial effects.

Another parameter important to sludge thickening processes is the Sludge Volume Index (SVI). This number indicates potential settling and compaction characteristics of the sludge solids. A high index indicates a bulking sludge that is difficult to dewater and compact (36).

The thickener solids loading rate affects the degree of sludge compaction. It is related to the Sludge Volume Index discussed above and the volatile solids concentration; a high SVI or volatile matter concentration requires a low solids loading rate. For sewage sludges the following loading rates are generally recommended:

| | |
|---|---|
| Primary sludge | 22 lbs./sq.ft./day |
| Primary + trickling filter sludge | 15 lbs./sq.ft./day |
| Primary + waste activated sludge | 8-12 lbs./sq.ft./day |
| Waste activated sludge | 4 lbs./sq.ft./day |

Loadings for industrial sludges vary greatly, so laboratory and pilot-plant tests are recommended to determine the exact design parameters. Eckenfelder and O'Connor present two examples of the variability of industrial sludge loadings (5): (1) an anaerobic packing house sludge with an SVI of 50 to 100 was loaded at 50-85 pounds per day per square foot of thickened area and (2) an anaerobic dairy sludge with an SVI of 100 to 300 was thickened at loadings of 25 to 35 pounds per day per square foot.

For best results, the following points should be considered in the design of wastewater sludge thickening tanks:

1. At secondary waste treatment plants, thickening of mixed sludges (primary and secondary) should be considered. Secondary sludges normally release their water slowly, but mixtures of secondary and primary and/or digested sludge seem to respond well to thickening.

2. Thickening tanks generally should be deep (15 feet), be of circular design, have inlet facilities that dissipate the entrance velocities, and have a single sludge outlet pipe with short suction connections(65).

3. The liquid displacement period in thickeners is of secondary importance for all sludges, but a minimum detention time of 6 hours and a hydraulic overflow rate of 400 to 800 gallons per square foot per day are recommended.

The quality of the overhead liquid removed from the sludge solids is important in any thickening operation because this liquid is usually returned to the treatment processes. Generally, the overhead quality is similar to that of raw sewage, 150 to 300 mg/1 suspended solids and a Biochemical Oxygen Demand (B.O.D.) of about 200 mg/1. A well-operated thickener should have a minimum of anaerobic decomposition and a solids capture exceeding 90 percent; using these guides the overflow returned to the primary clarifiers or the aeration tank of an activated sludge system should not present an operational problem.

Performance - Gravity thickening of waste activated and mixed sludges was recently evaluated in an experimental picket thickener at the Chicago Sanitary District. The following conclusions resulted(56):

1. Picket thickeners can be successful. Table 5.1 shows that thickeners with pickets increased the solids concentrations from 33 to 100 percent over the concentrations obtained with standard gravity thickening tanks. The advantage of including primary sludge and the decrease in concentration with increasing SVI are also demonstrated.

2. Wet air oxidation ash used as a weighting agent did not improve thickening.

3. Treating the thickner feed with a cationic polyelectrolyte permitted solids loadings two to four times greater than those possible with untreated feed. However, no increase in sludge compaction was noticed until the polymer dosage was increased beyond 10 pounds per ton of dry solids.

## Table 5.1

## Average Results of Experimental Picket Thickner

| Feed | | | Thickened Solids (%) | |
|---|---|---|---|---|
| Type of Sludge | Solids (%) | Loading (psfd)* | Picket Thickener | Standard Thickener |
| Activated (SVI = 74) | 1.06 | 21 | 3.0 | 1.8 |
| Activated (SVI = 97) | 0.87 | 20 | 2.8 | 1.4 |
| 50% Activated Preliminary | 1.10 | 20 | 4.4 | 3.3 |

*Pounds per square foot per day

Keefer successfully investigated Densludge thickening at Baltimore; raw primary, waste activated, and trickling filter sludge was concentrated to as much as 8.5 percent solids(110). The optimum operating criteria were as follows: (1) the mixed sludge was diluted with plant effluent to a concentration of 1400 to 3200 mg/1, (2) the detention time was 1.5 hours, (3) surface loading was 790 gallons per square foot per day, and (4) the suspended solids loading was 14 to 14.5 pounds per square foot per day. This performance was a 45 percent improvement over conventional plant thickening.

Beaumont, Texas, reported very good thickening performance(108). Normal operations produced a thickened primary and trickling filter sludge having 8.7 percent solids. Controlled operations where the dissolved oxygen (D.O.), settleable solids, and sludge blanket level were closely watched, produced a concentration of 11.5 percent. The thickening tank was kept in an aerobic state by adjusting the amount of filter humus and well-aerated plant effluent pumped to the tank. Loading rates between 2 and 14 pounds per square foot per day produced a consistent sludge compaction. The thickener overflow, averaging 130 ppm B.O.D. and 98 ppm suspended solids, was discharged to the secondary trickling filters with no effect on B.O.D. removal.

The Cleveland Southerly Sewage Treatment Plant thickens waste activated sludge in deep Dortmund tanks from a feed of 1.72 percent to 2.7 percent. Ninety-eight percent solids capture was attained by batch operation with a detention period of 7.5 hours(27). At Cleveland Easterly, standard final settling tanks have been operated on a continuous feed basis for six years. They increased the average concentration of waste activated sludge from 1.64 to 2.49 percent. Overflow from the thickening tanks contained a very low (26 mg/1) suspended solids concentration(27).

Torpey presented the results of thickening mixed sludges at the Bowery Bay Sewage Treatment plant over a 19 month period (107). He reported that average solids concentrations of 11.2 percent for primary and modified activated sludge were achieved with less than 24 hours' detention. The concentration attained with a mixture of primary and conventional activated sludge was 6 percent total solids. Torpey recently disclosed that much greater concentrations are possible by adding digested sludge to the mixture of raw sludges. Several New York City sewage treatment plants have used chlorine in thickening tanks during the summer months. As quoted by Wirts, Donaldson considered chlorine as a useful tool to improve the thickener operation during summer months or when the settling characteristics of the sludge were below average(27).

At Hagerstown, Maryland, lime used in conjunction with sludge aeration increased activated sludge thickening from a solids concentration of 0.6 to 3.5 percent (201). The dose was 180 pounds per ton. In laboratory and pilot plant studies, Caron and Carpenter demonstrated a polyelectrolyte dosage of 1.2 pounds per ton could increase boardmill sludge thickening rates by 55 percent. A 2.4 pound per ton dose increased the rate for deinking sludge by 140 percent(194). The tank overhead was clearer than a control but the solids concentration was unchanged.

Economics - A good economic case can be made for gravity thickening because it offers the chance of reducing sludge volumes by one-half. The reduced volume of sludge in turn results in reduced costs of digestion and sludge dewatering. Beaumont, Texas, reports savings of $175,000 in plant construction costs by use of thickeners which allowed reduced digester capacity (from 510,000 cubic feet to 240,000 cubic feet)(108). In addition thickening solved some digester operation problems, such as the production of excessive supernatant liquor. Burlington, North Carolina, saved an estimated 11.3 percent on the construction cost of a sewage treatment plant by incorporating thickening and high rate digestion(116).

Specific costs of thickening equipment and annual costs per ton of sludge handled vary widely depending on local conditions. In comparison with thickening activated sludge by pressurized air flotation, the initial costs incurred with gravity thickening are greater but the operation costs less(65). At large plants, maintenance and operating costs for gravity thickening are about $2 per ton of dry solids. In general, total annual costs (capital and operating) vary between $1.50 and $5.00 per ton of dry solids.

Summary - Gravity thickening of waste sludges has been successfully practiced for many years. Its basic purpose is to reduce sludge volumes; this in turn allows reductions in the costs of sludge digestion and dewatering. The capacity of the digesters is increased, their heat requirement is reduced, and they operate more efficiently. The cost of dewatering sludge in mechanical equipment, particularly vacuum filters, is less because production rates rise with increased feed solids concentrations and chemical costs are reduced. Since thickening reduces the volume of digester supernatant liquor, the overall treatment plant efficiency is improved because less solids (contained in the supernatant liquor) are returned to other treatment processes. Liquid which would be returned as supernatant liquor is returned as thickener overflow, a much more desirable condition(116).

While gravity thickening has some important advantages, it also has some possible disadvantages. First, thickening tanks must be well operated or odors will develop; septic-bulky sludge will form, resist compaction, and float to the surface of the tanks, and the entire treatment plant efficiency could be impaired by the recycle of thickener overflow containing a high concentration of B.O.D. and suspended solids. Anaerobic conditions can be minimized by the addition of aerated effluent, dilute biological sludges, or chlorine, and by proper sludge pumping procedures. Degasifying the feed sludge by vacuum has been proposed as an efficient method of enhancing solid-liquid separation and sludge compaction. Another disadvantage is the capital cost of gravity thickening units. It is substantial but often justifiable because of other process cost savings. Air flotation units may be cheaper, but they have other disadvantages that often preclude their use, particularly with non-activated sludges.

Considerable "art" is still involved in the operation of gravity thickening tanks. Careful observation and reporting by operators is needed to insure the best possible operation. Additional improvements in the thickening "art" or "science" are needed. Mancini suggested that new research is needed to develop a bench-scale continuous-flow thickening test that will lead to reliable design parameters for full-scale units(92). Also, increased compaction of solids is usually a desirable goal. Perhaps mechanical dewatering before incineration could be eliminated if a higher degree of thickening than is possible today were achieved. Improved designs of mechanical facilities should be considered. Combining various sludges or tank overflows with or without settling aids has proven to be a successful technique. Torpey's discussions of mixed sludge thickening, including the addition of digested sludge to raw sludge have indicated increased solids concentrations are possible(107).

The control of odor in raw sludge thickening operations deserves more attention because this is a major problem at many wastewater treatment plants.

Gravity thickening definitely has a future in the handling of wastewater solids. It particularly offers a good way to thicken mixed sludges at a low operating cost.

## B. Flotation Thickening

General - **Flotation** thickening units are becoming increasingly popular at sewage treatment plants, especially for handling waste activated sludges. With activated sludge they have the advantage over gravity thickening tanks of offering higher solids concentrations and lower initial cost for the equipment.

Four methods of flotation, using rising gas bubbles to increase the buoyance of solid particles, are used in the waste treatment field: (1) dispersed air flotation where bubbles are generated by introducing air through a revolving impeller or porous media, (2) dissolved air-pressure flotation where air is put in solution under elevated pressures and later released at atmospheric pressure, (3) dissolved air-vacuum flotation which applies a vacuum to wastewater aerated at atmospheric pressure, and (4) biological flotation where the gases formed by natural biological activity are used to float solids. Only dissolved air-pressure flotation and natural biological flotation will be discussed in this section on thickening. The two other processes generally are more applicable to wastewater clarification because significant increases in sludge solids concentrations are difficult to achieve.

### Dissolved Air-Pressure Flotation

Theory - The objective of flotation-thickening is to attach a minute air bubble to suspended solids and cause the solids to separate from the water in an upward direction. This is due to the fact that the solid particles have a specific gravity lower than water when the bubble is attached.

Dissolved air flotation depends on the formation of small diameter bubbles resulting from air released from solution after being pressurized to 40 to 60 psi. Since the solubility of air increases with pressure, substantial quantities of air can be dissolved(121). In current flotation practice, two general approaches to pressurization are used: (1) air charging and pressurization of recycled clarified effluent or some other flow used for dilution, with subsequent addition to the feed sludge; and (2) air charging and pressurization of the combined dilution liquid and feed sludge(121).

Air in excess of the decreased solubility, resulting from the release of the pressurized flow into a chamber at near atmospheric pressures, comes out of solution to form the minute air bubbles (average diameter 80 microns). Sludge solids are floated by the air bubbles that attach themselves to and are enmeshed in the floc particles(5). Rich observed that entrapment of rising air bubbles in the floc particle is the predominant action with flocculent materials such as activated sludge. Contact of bubble and particle by adhesion has more significance with non-flocculent solids(6). The degree of adhesion depends on surface properties of the solids. Ettelt states that complete attachment of all the air bubbles is theoretically possible but is not achieved(121).

When released into the separation area of the thickening tank, the buoyed solids rise at a rate similar to that shown in Figure 5.V(121). Hindered conditions analogous to gravity sedimentation occur and can be called hindered separation or flotation. The upward moving particles form a sludge blanket having a solids concentration gradient. Figure 5.VI by Katz and Geinopolos shows a typical gradient plotted for waste activated sludge(65a). The degree of sludge thickening depends on the compressional force and the surface active properties of the solids resisting compression(121).

Parameters - The primary variables for flotation thickening are: (1) pressure, (2) recycle ratio, (3) feed solids concentration, (4) detention period, (5) air-to-solids ratio, (6) type and quality of sludge, (7) solids and hydraulic loading rates, and (8) use of chemical aids.

Air pressure used in flotation is important because it determines air saturation, size of the air bubbles formed, and it influences the degree of solids concentration and the subnatant (separated water) quality. In general, increased pressure, or air, produces greater float (solids) concentrations and a lower effluent suspended solids concentration. There is an upper limit, however, because too much air breaks-up fragile flocs. Mayo recommended 0.03 cubic feet per square foot of tank surface area per minute(124).

The recycle ratio and feed solids concentration are inter-related. Additional recycle of clarified effluent does two things: First, it

Figure 5.V

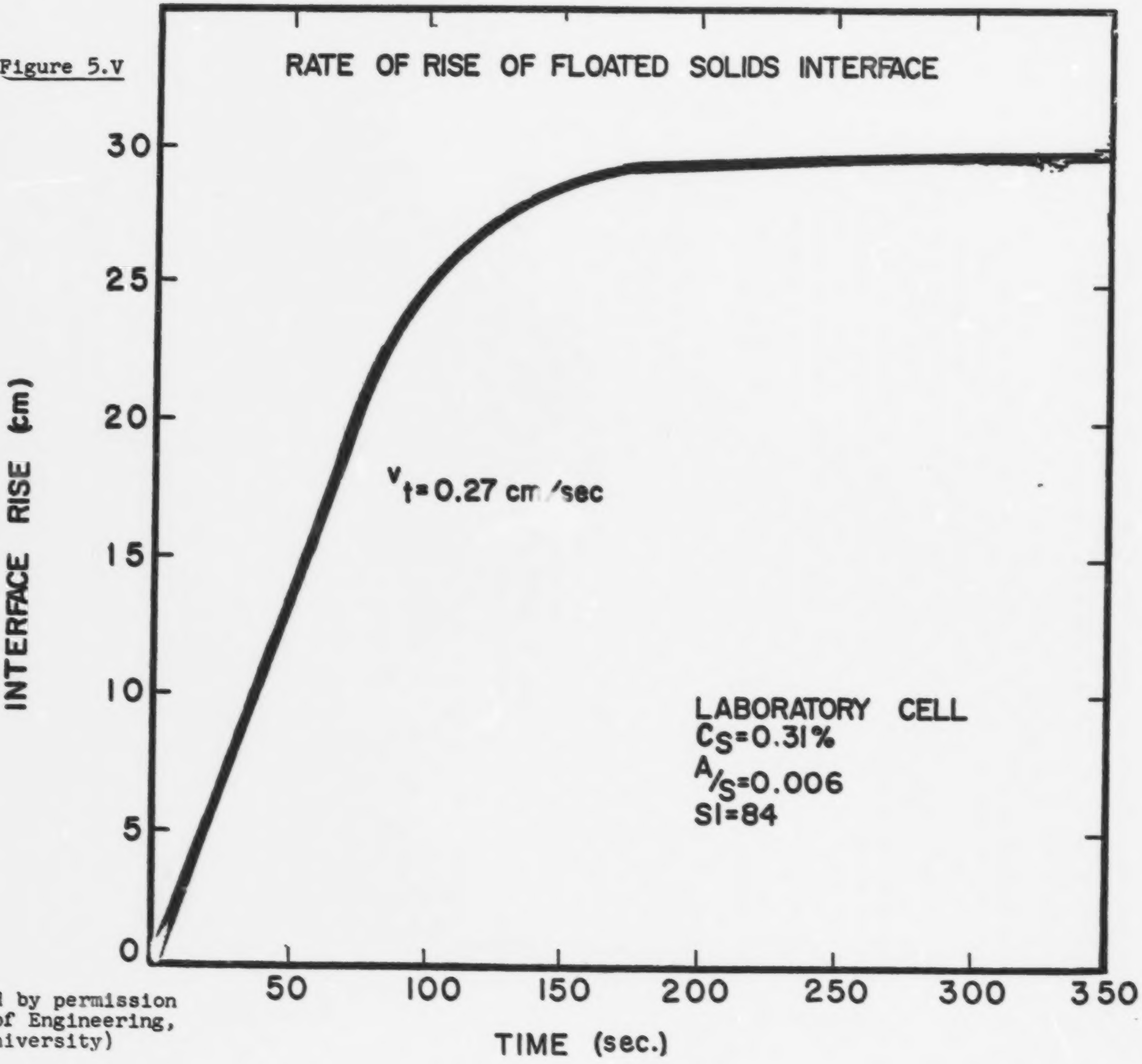


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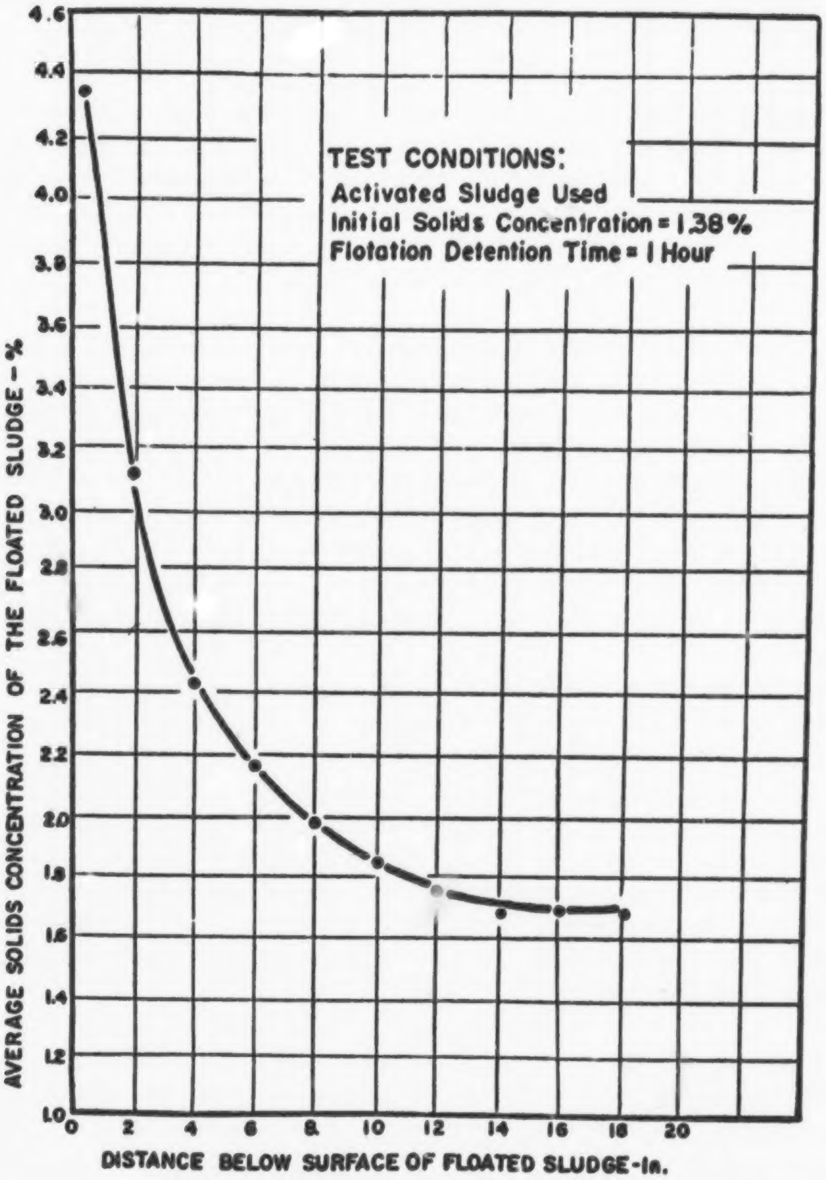
Figure 5.VI



—Solids concentration gradient in the floated sludge blanket (in. × 2.54 = cm).

(Reprinted by permission from Vol. 36, No. 4, p. 409, April 1964, J. Water Pollution Control Federation) allows a larger quantity of air to be dissolved because there is more liquid and second, it dilutes the feed sludge. Dilution reduces the effect of particle interference on the rate of separation. At the Chicago Sanitary District, 40 percent recycle proved to be optimum(121). Katz presented the data shown in Figure 5.VII depicting greater rise rates with increasing recycle ratios(122). Experience has also proven that dilution of the feed sludge to a lower concentration increases the concentration of the floated solids(119).

The concentration of sludge increases and the effluent suspended solids decrease as the sludge blanket detention period increases(5). Figure 5.VIII shows data by Katz that emphasizes the importance of thickening time(122). In plant tests there was a rapid increase in solids concentration with time up to 3 hours. Beyond 3 hours no additional thickening was observed.

As indicated in Figure 5.IX the air-to-solids ratio is a parameter that influences the sludge rise rate. Increasing concentrations of air/solids causes increases in floated solids production(121). Eventually with unlimited use of air, a ratio can be reached where no further increase in concentration would be possible. Ettelt reported the effluent (subnatant) solids concentration was not dependent on the air-to-solids ratio except for very low air input rates or very high solids loading rates(121). Mayo suggested that 0.02 pounds of air per pound of solids was an effective ratio(124).

Similar to gravity sedimentation, the type and quality of sludge to be floated affects the unit performance. Flotation thickening is, as stated before, most applicable to activated sludges but higher float concentrations can be achieved by combining primary with activated sludge. Equal or greater concentrations may be achieved by combining sludges in gravity thickening units. A high sludge Volume Index (SVI), representing a bulky sludge, results in poor thickener performance. Figure 5.X describes the importance of this parameter as it applies to the flotation of activated sludge at the Chicago Sanitary District (121).

Unit loading rates naturally affect the performance of flotation thickening units. Figure 5.XI shows a typical example of relating unit loadings, solids production, and floated solids recovery at the Chicago Sanitary District(121). In general, higher loadings impair the performance of thickening units.

Figure 5.VII

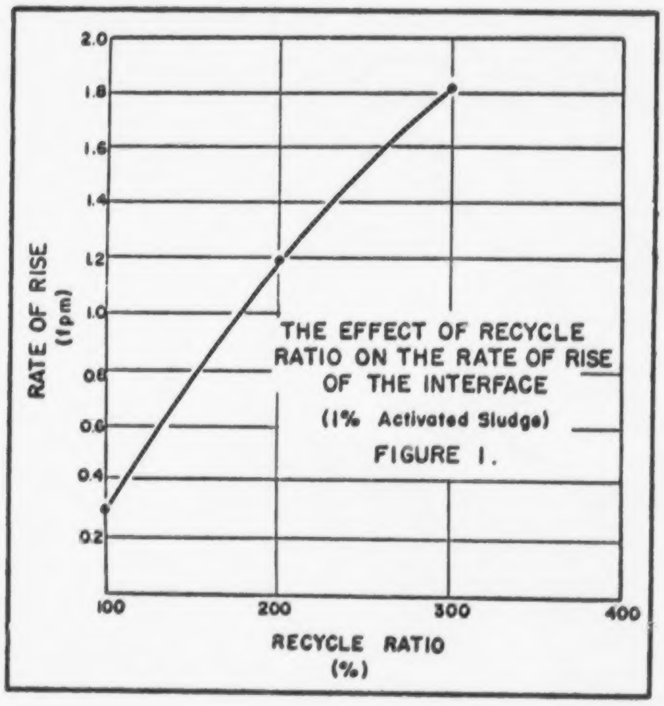


Figure 5.VIII

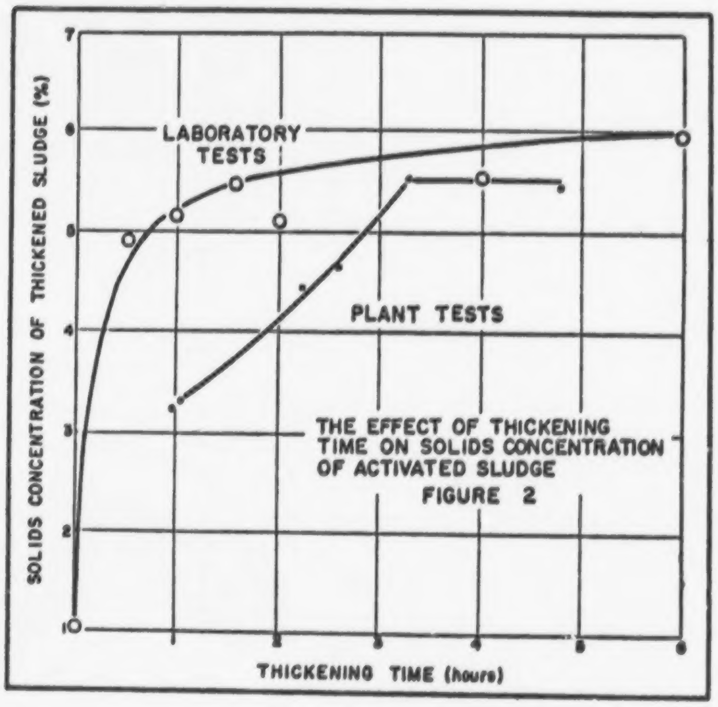


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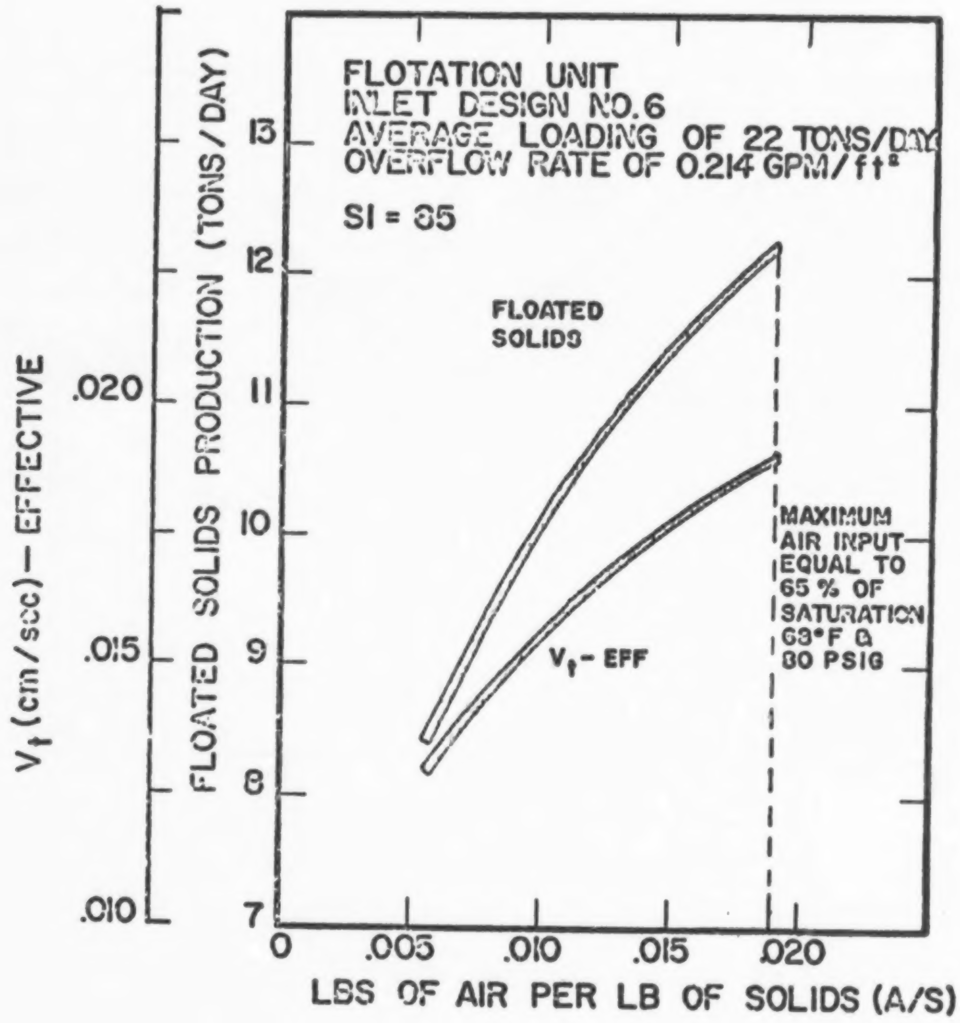
Figure 5.IX



Effect of air content on floated solids production and effective terminal velocity at constant overflow rate.

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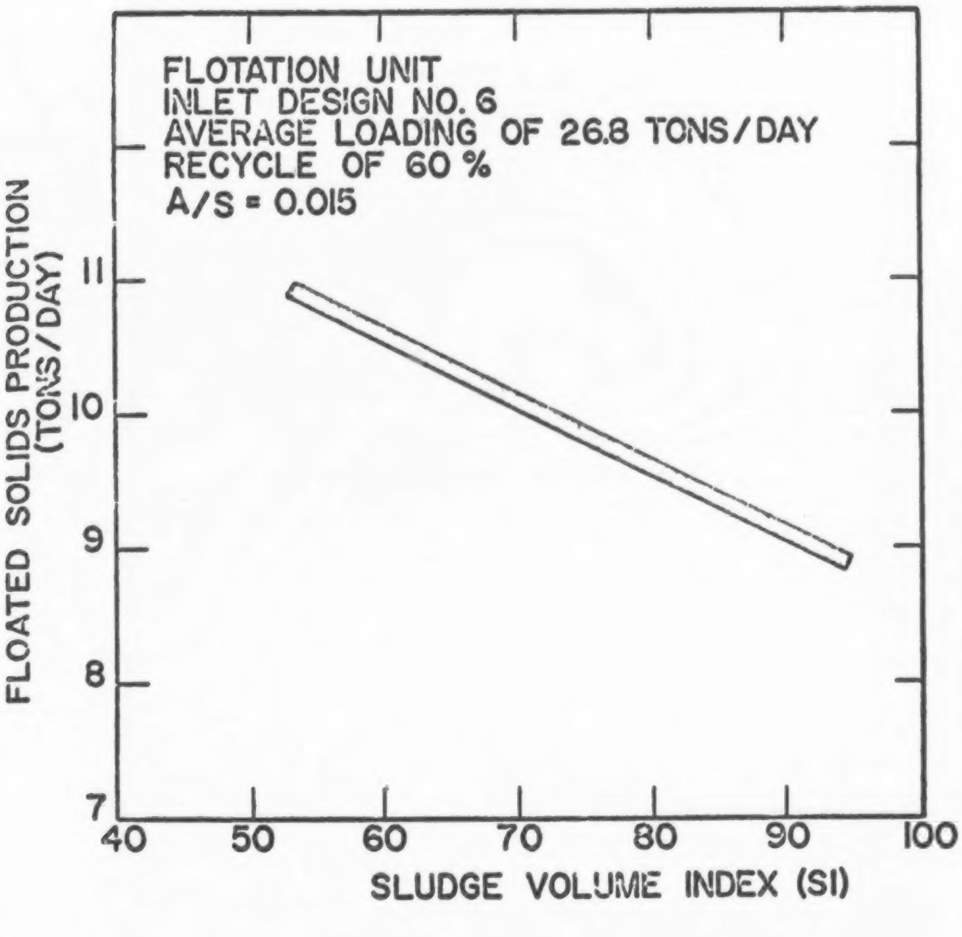
Figure 5.X



Effect of Sludge Volume Index on floated solids production.

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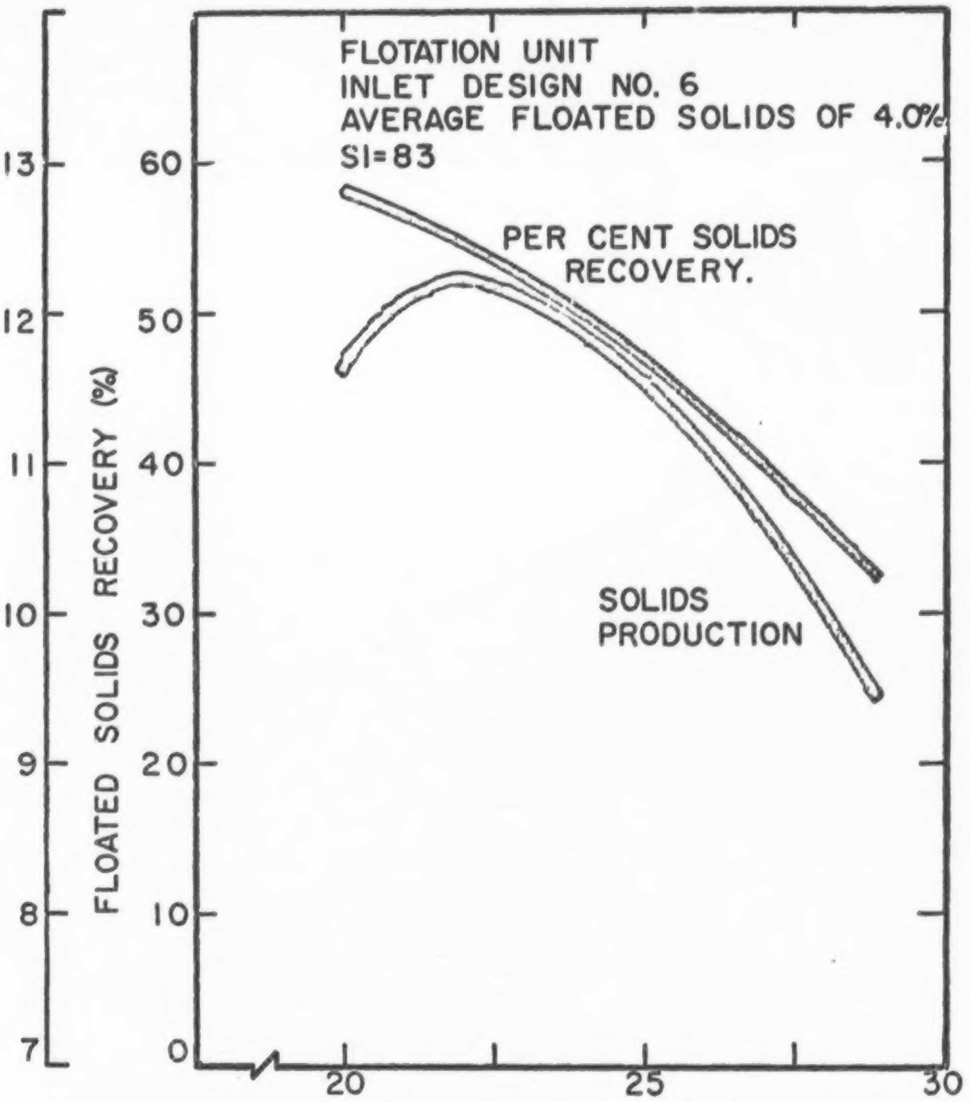
Figure 5.XI



Effect of loading on floated solids production and recovery.

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Many different chemicals have been used in various air flotation systems. Industrial processes, particularly in the mining industry, use frothers and collectors to lower interfacial tension, and they use promoters to improve the effect of collectors(6). In the waste treatment field, flocculating chemicals have agglomerated solids into stable flocs that promote increases in the terminal velocity and facilitate capture of gas bubbles. The overall effect is to increase the allowable solids loadings, increase the percentage of floated solids, and increase the clarity of the effluent. Cationic polyelectrolytes have been the most successful chemical used in sewage sludge thickening.

Design - Solids loading is the design parameter governing the sludge surface area of the flotation thickening unit(65a). This and other design parameters are evaluated in pilot plants by the two major manufacturers of air flotation equipment. Scale-up to full scale units does not always correlate accurately because of flow turbulence in the pilot plants. Laboratory tests usually precede pilot plant tests for the purpose of determining recycle ratios, chemical treatment dosages, and the susceptibility of sludge thickening by dissolved air flotation.

The principal components in a flotation system are: (1) a pump to increase pressures for greater air solubility, (2) a retention tank where air and liquid are mixed under pressure for 1 to 2 minutes, (3) a pressure release valve, and (4) the flotation unit containing a quiescent zone and a sludge withdrawal mechanism. Tank inlet design is one of the most critical features of the flotation unit. A design that encourages reduced turbulence and provides greater bubble-solid confinement with maximum adhesion efficiency is desirable (121). Turbulence can cause a separation of bubbles from the solids resulting in particle settling rather than flotation. At the Chicago Sanitary District the use of cylinders to reduce inlet velocities and to disperse the flocs vertically was successful(121).

Performance - A pilot plant comparison of gravity thickening versus air flotation thickening was described by Katz and Geinopolos(65a). Mixtures of primary and activated sewage sludge were thickened to an average of 4.5 percent in the gravity unit and 6.0 to 6.5 percent in the flotation unit. The gravity unit was loaded at 8 pounds per square foot per day and the flotation unit with 20 to 30 pounds per square foot per day.

Extensive flotation thickening evaluations at the Chicago Sanitary District resulted in the following conclusions(121):

1. Waste activated sludge can be thickened to a higher solids concentration by flotation (4%) than by gravity settling (2%).

2. Maximum floated solids production and solids recovery was obtained at a loading of 13.5 pounds per square foot per day.

3. Optimum combined, floated plus settled, sludge thickening resulted in a solids concentration of 3 percent and a total solids capture of 92.5 percent.

4. The use of a cationic polyelectrolyte at a dosage of 20 pounds per ton doubled the floated tonnage, increased solids capture to 99.6 percent, and increased the solids concentration to 3.9 percent. Figure 5.XII shows the effect of the flocculent dosage over a wide range.

The importance of the air content has also been demonstrated at Chicago. Table 5.2 presents data showing the performance at 50 percent air saturation and 75 to 82 percent saturation(56):

Table 5.2

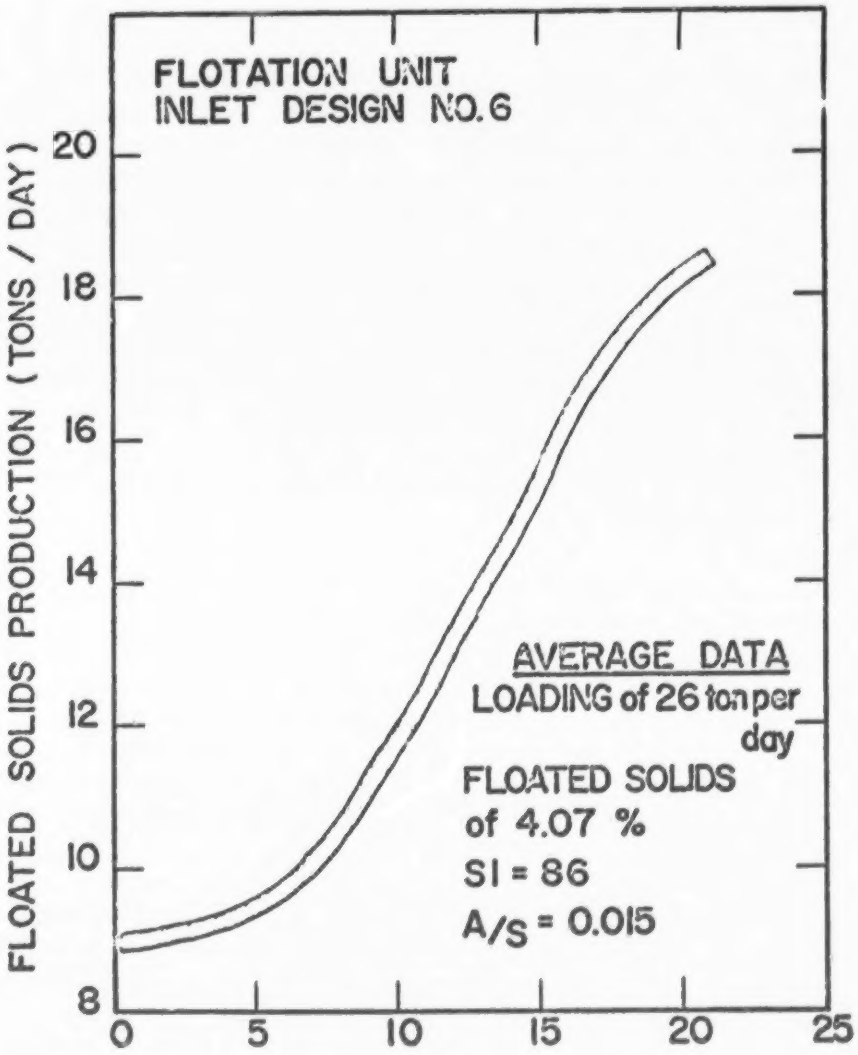
| 50% Saturation | | 75 to 82% Saturation |
|---|---|---|
| 0.42 | Floated to settled sludge ratio | 0.67 |
| 11.4 | Solids loading in lbs./sq.ft./day | 13.8 |
| 3.2 | Floated solids concentration | 3.5 |

Braithwaite discussed the successful use of polymeric flocculents as an aid to flotation thickening of waste activated sludge at Warren, Michigan(120). In general, polymers permitted consistent and reliable treatment and produced thickening results that would be impossible to achieve without polymers. A summary of the Warren data is as follows:

| | Without Chemical Aids | With Chemicals Aids |
|---|---|---|
| Solids removal rate (lbs./sq.ft./hr.) | 0.9 | 3.34 |
| Solids concentration (%) | 4.1 | 6.2 |

Figure 5.XII

Effect of Cationic Flocculant on
Solids Production



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The data indicated a 73 percent reduction in theoretical flotation unit surface area is possible with the use of chemicals.

Rudolfs investigated many chemicals as aids to flotation thickening of activated sludge(33). He found that calcium hypochloride was particularly effective; a dosage of 16 pounds per 1,000 gallons of sludge (364 lbs./ton) increased the solids concentration from 1.05 to 3.75 percent after 6 hours compaction. Other chemicals investigated by Rudolfs included chlorine, sulfuric acid, carbon dioxide, and nitrogen. He was looking for a material that would flocculate and dehydrate solids as well as to allow gases to form and rise to the surface.

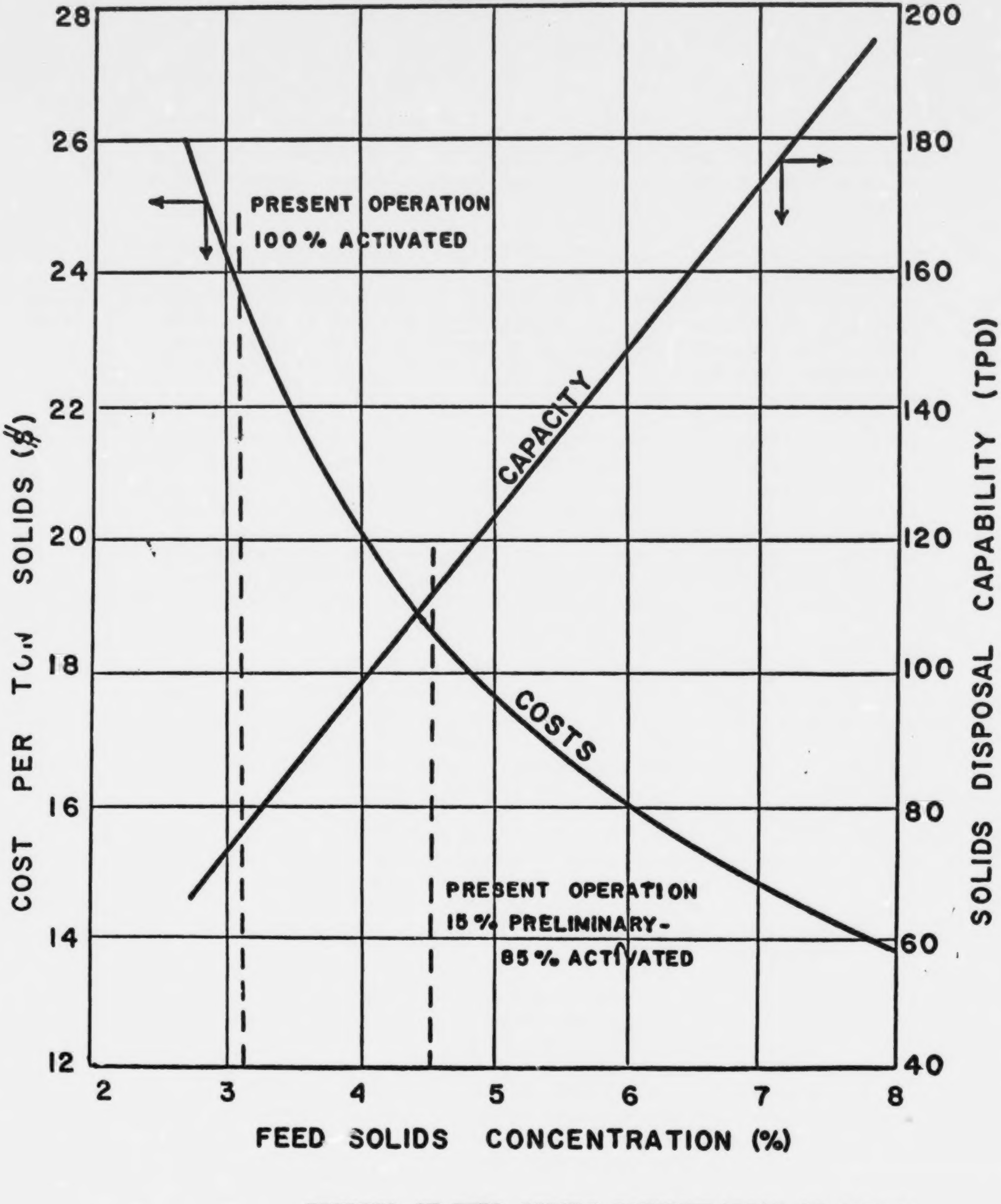
Economics - Flotation thickening is a relatively new process installed at very few sewage treatment plants. As a result the literature contains very few references regarding costs. However, an estimate of the operating cost without the use of chemicals is $4 to $5 per ton of solids. Because chemicals could cost another $5 to $6 per ton, the operating costs using chemicals would be double the non-chemical cost. In general, it is accepted that the initial cost of flotation is lower than gravity thickening but the operating cost is higher. The operating cost of flotation units should be less than the operating costs of centrifuges unless chemicals must be used. One leading manufacturer of flotation units specifically recommends the use of chemicals. In general, the total annual cost of air flotation thickening varies from $6 to $15 per ton of dry solids.

Any evaluation of thickening should consider the economy resulting from the production of a thicker sludge. This will include the conventional items associated with a thicker sludge such as lower digestion costs and lower vacuum filtration costs. At the Chicago Sanitary District air flotation thickening has a tremendous influence on sludge digestion costs(56). As illustrated in Figure 5.XIII, a 3 percent sludge has a digestion disposal cost of about $24 per ton while a 4.5 percent sludge cost less than $19 per ton of dry solids.

Summary - The need for an effective process to thicken waste activated sludge has long been recognized and is now available. While dissolved air flotation units were first applied to clarification operations, they have proven their value for thickening activated sludge to a concentration higher than is possible in gravity thickening tanks. These units can also be used for thicken-

②

Figure 5.XIII



EFFECTS OF FEED SOLIDS CONCENTRATION ON SOLIDS DISPOSAL CAPABILITY AND UNIT COSTS OF HIGH RATE DIGESTION PLANT AT CHICAGO SOUTHWEST PLANT.

(Reprinted by permission from Vol. 38, No. 2, p. 249, Feb. 1966, J. Water Pollution Control Federation) ing mixed primary and activated sludge, but they do not do this job as effectively as gravity thickening units unless the percentage of primary sludge is very low.

Flotation thickening has the disadvantage of having many parameters that can affect its performance. As a result inconsistent thickening may occur by changes in such factors as sludge particle size, sludge volatile concentration, sludge age, and quality of recycle water. The use of flocculents as recommended by one manufacturer can correct this problem but at cost that could double the total operating cost.

Basically, flotation processes are not as simple, consistent, and economical as other thickening processes. As a result its use will be limited generally to what it does best - thickening waste activated sludge or low specific gravity, non-activated industrial waste solids. Even then, unless activated sludge is disposed of separately, gravity thickening could be more efficient because the sludges are usually blended before dewatering in mechanical equipment. Blending might as well be performed in gravity thickening tanks.

### Biological Flotation

General - The flotation of organic sludges after extended storage in a tank (without the aid of heat) is a well-known phenomenon. Improvement on this natural flotation technique by controlling heat and detention is best illustrated by the Laboon Process(131). This process, as designed for the Alleghany County Sanitary Authority (Pittsburgh, Pa.) consists of the following steps:

1. Disintegration of the raw primary sewage sludge (5-10% solids) to prevent clogging of pumps and equipment in subsequent sludge handling processes.

2. Heating of the sludge to 95°F in heat exchangers operated at 15 psi.

3. Concentration of the sludge by biological means for 5 days. Escaping gases buoy and compact the sludge in the concentration tanks.

4. Separation of subnatant liquor on the fifth day and pumping the concentrated sludge to the Incineration Building for subsequent incineration (discussed further in the Combustion chapter of this report).

Parameters important to biological flotation include: (1) sludge temperature, (2) detention period, (3) type of sludge and its volatile content, and (4) sludge pH. Laboratory studies using numerous sludges indicated that 35°C was the optimum temperature and 5 days was the optimum detention period(129). Activated sludge could not be concentrated because it would not float. Some mixtures of primary and activated sludge could be concentrated to some degree by flotation, but settling occurred during extended detention periods. High sludge pH inhibited bacterial action resulting in insufficient gas to cause solids flotation.

Performance - A natural biological flotation pilot plant was operated by Laboon for one year. Raw primary sludge was concentrated from 4 percent to 20 percent solids by his process. This sludge could be dewatered on vacuum filters without prior chemical treatment and it could be digested(129). The concentration tank subnatant (separated liquid) had an average B.O.D. of 2970 ppm and suspended solids of 4000 ppm. It was estimated upon recycle to the head of the treatment plant that this subnatant liquid would increase the total sewage flow by less than 7 ppm B.O.D. and suspended solids by less than 10 ppm. No solids build-up from the subnatant recycle was expected(23). Actual plant scale operation of the Laboon Process at the Alleghany County Treatment Plant approximates the pilot plant performance. An average sludge concentration of 18 percent is produced from a feed sludge of 10.7 percent.

Ashland, Ohio, thickens sludge to 15 percent by biological flotation without heat. This enabled them to incinerate their sludge in a multiple hearth furnace with the use of supplemental fuel(129). The Laboon Process is being used to thicken raw primary and waste activated sludge at Charlotte, North Carolina(66). Raw sludge containing considerable industrial wastes is concentrated to 10 to 14 percent solids before digestion.

Summary - Natural biological flotation is being successfully used to concentrate raw sludge at a few sewage treatment plants. At Pittsburgh it makes possible the goal of sludge incineration without prior mechanical dewatering. What the overall sludge handling costs are at this plant has not been reported in the literature. Therefore, an estimate of the suitability of the Laboon Process in comparison with other systems cannot be made precisely. The thickening process itself probably is fairly expensive because of the sludge heating, the lengthy detention period, and the need to blend sludges from the various concentration tanks in order to insure a uniform feed to the incinerators. Another disadvantage associated with any raw sludge thickening process is the possibility of odor development. Enclosed units with a system to draw gases off into a deodorizing chamber are required.

Biological flotation as a sludge concentration technique seems limited unless improvements are made in the process. Secondary sludges apparently do not respond well and on the surface the cost appears high. Odors must be closely controlled. But, it has demonstrated the advantage of eliminating the need for a mechanical dewatering step ahead of sludge incineration. Perhaps with the use of chemical additives and/or waste heat from incineration units, the process can become less expensive and more efficient.

## C. Centrifugation

General - The use of centrifuges to thicken and dewater sludge is not a new development. For many years this equipment has been successfully used by the process industries. Centrifuges were first evaluated for waste treatment applications nearly 40 years ago, but only recently were they installed for regular use at wastewater treatment plants.

This section discusses only performance data for the thickening application of centrifuges. The dewatering chapter of this report discusses centrifugation theory, parameters, and economics. Dewatering can be distinguished from thickening by assuming that it is the dehydration stage where solids are not fluid and can't be pumped. Thickened solids are fluid and can be pumped.

Performance - One of the first reports of sludge thickening by centrifugation describes an evaluation at Sioux Falls, South Dakota(23, 125). They investigated a system where activated sewage sludge containing 0.5 to 0.8 percent solids was passed over a vibrating 65-mesh wire-cloth screen and then thickened in a centrifuge. Solids discharged from the bowl-type centrifuge had an average concentration of 5 to 7 percent. The centrate (separated liquid), containing 250 ppm solids, was recycled to the primary clarifers with no impairment in overall treatment plant efficiency. The total annual cost of the centrifuge operation was estimated to be $4.37 per ton in 1954. Power costs accounted for 20 percent of this total and labor, 26.5 percent.

Centrifuge thickening of waste activated sludge was extensively studied at the Chicago Sanitary District. Ettelt and Kennedy reported that both disc-type and solid-bowl centrifuges were evaluated(56). The disc-type machine concentrated the activated sludge to about 7.0 percent at 6,000 rpm, but operational problems made its use impractical. Clogging of the sludge discharge nozzles required repeated maintenance. Vibrating screens could not remove a sufficient amount of oversized solids to prevent clogging; rotary screens were more effective, but at low flow-through rates. The centrifuge captured 87 to 97 percent of the feed solids at a feed rate of 3,600 gallons per hour(gph).

Two solid-bowl centrifuges were also evaluated, using Chicago activated sludge; one was a concurrent machine, the other a countercurrent(56). Using activated sludge alone, the concurrent machine thickened sludge to about 7 to 7.5 percent. The countercurrent machine thickened the sludge to about 6.6 to 7.0 percent. A 1:1 mixture of preliminary and activated sludge was thickened to 9.8 percent. By lowering the liquid level in the centrifuge, activated sludge was thickened to 16 percent, but the solids capture was very poor. Figure 5.XIV shows the decrease in solids capture with increasing degrees of thickening resulting from lowering the liquid level.

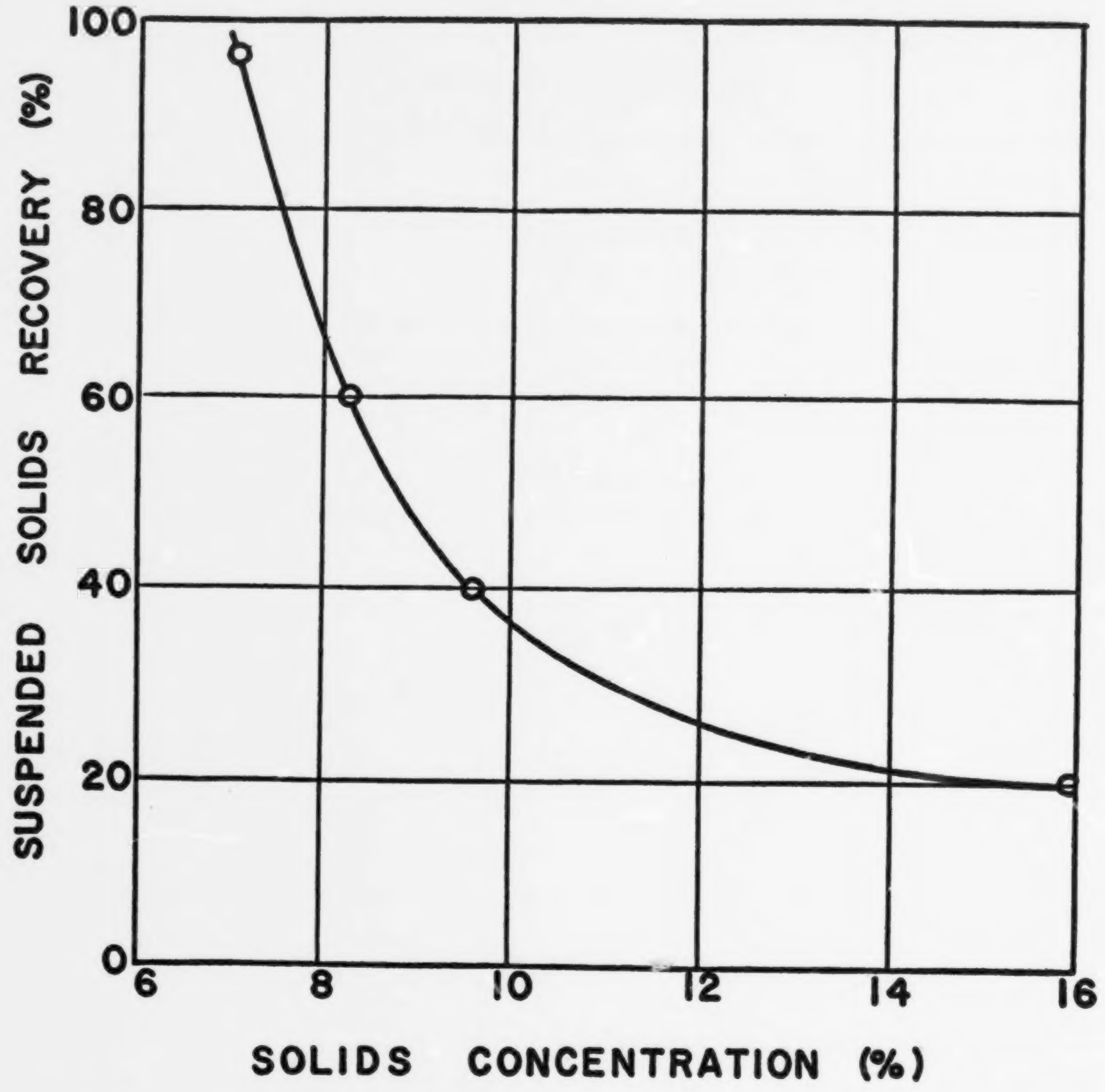
The use of cationic polyelectrolytes significantly improved the centrifuge performance as indicated by Figures 5.XV and 5.XVI(56). The use of these flocculents allowed significant increases in cake production and solids concentration. It is interesting to note the effect of sludge quality (SVI) and the blending of preliminary/activated sludge on the centrifuge performance. As shown in Figures 5.XV and 5.XVI, much higher production rates and solids concentrations are possible with a mixed preliminary and activated sludge. Also a sludge having a high SVI (indicating a low quality material) cannot be thickened as rapidly or to as high a solids concentration as a good-quality sludge can.

Solid bowl centrifuges operate with lower gravitational forces than disc centrifuges. While gravitational force is not the only factor in determining centrate clarity, the solid bowl machine does not usually produce a high quality centrate, in part due to the lower force. The solid bowl machines were evaluated at speeds between 1,340 and 2,700 rpm.

The Yonkers Sewage Treatment Plant of Westchester County, New York, has a very successful centrifuge thickening operation. They thicken digested, primary sludge prior to ocean barging. In the two year period 1961-1962, the sludge barge averaged 79 trips each year. During 1964-1965, after centrifuge thickening was adopted, the barge trips per year averaged 32.5(127).

At Yonkers, gravity settling is used to thicken a dilute primary sludge (0.35%) to about 8 percent before digestion. The average digested-sludge solids-concentration fed into the centrifuge is 4 to 5 percent. Thickening to 10 or 11 percent is done in the centrifuge; it could do more but at a higher level the sludge would not flow to the barge(127). It has been observed that a high-volatile sludge does not thicken as well as a low-volatile sludge.

Figure 5.XIV



DECREASE IN RECOVERY WITH CORRESPONDING INCREASE IN SOLIDS CONCENTRATION FROM LOWERING LIQUID LEVEL IN CENTRIFUGE. ACTIVATED (SVI=91)

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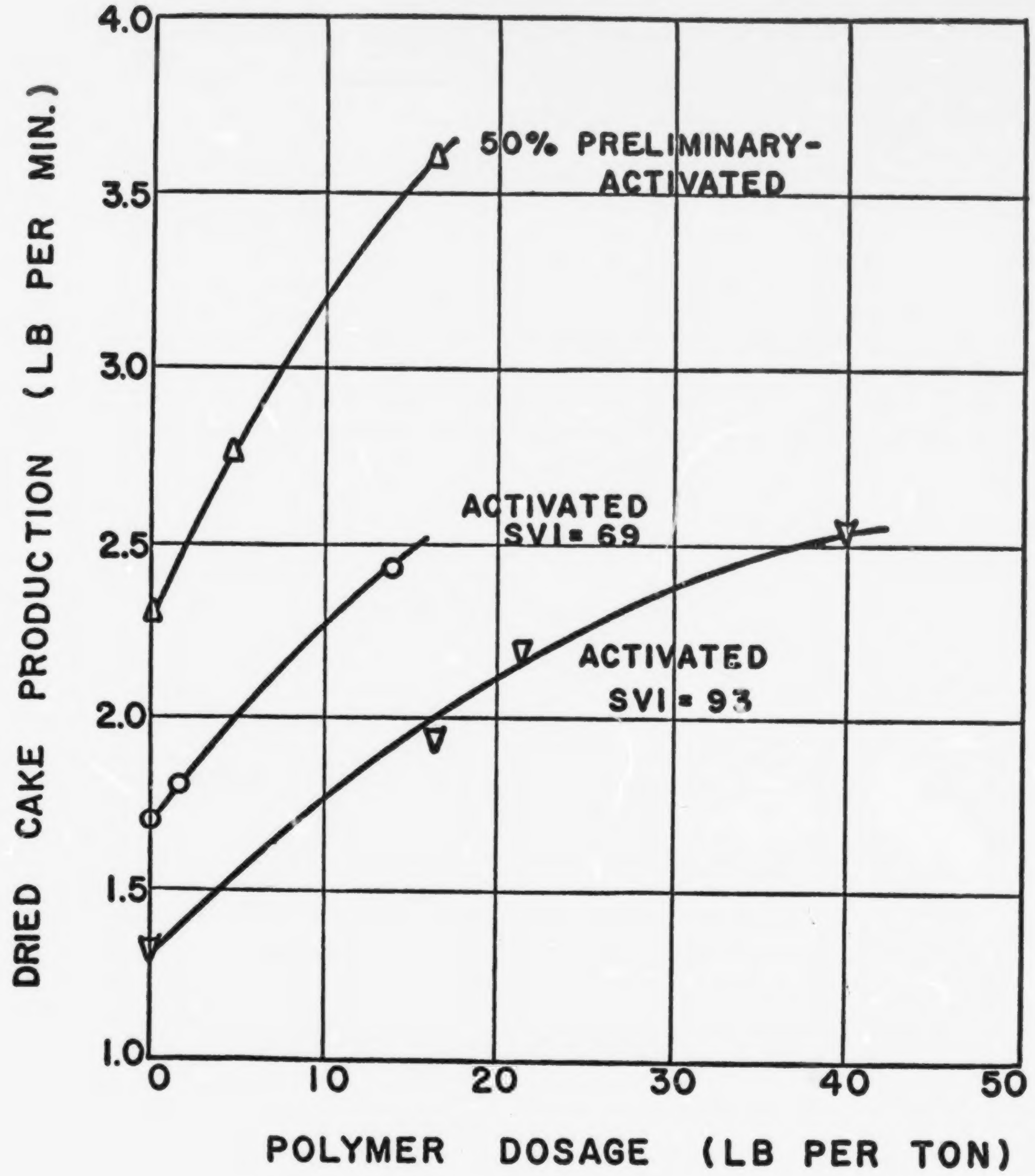
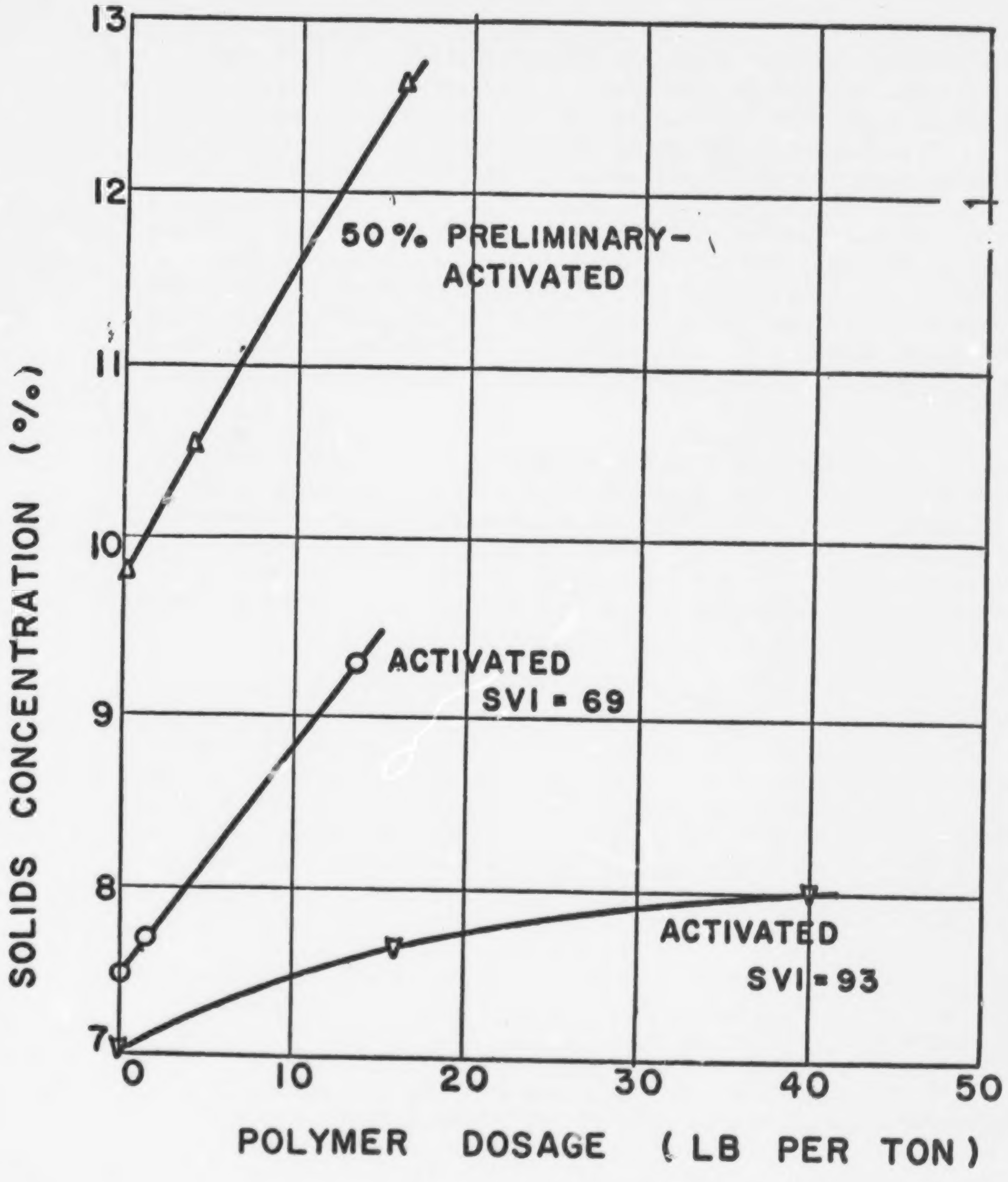
Figure 5.XV



EFFECT OF CHEMICAL ADDITION ON CAKE PRODUCTION BY CONCURRENT CENTRIFUGE. 90% SOLIDS RECOVERY.

(Reprinted by permission from Vol. 38, No. 2, p. 252, Feb. 1966 J. Water Pollution Control Federation)

Figure 5.XVI



EFFECT OF CHEMICAL ADDITION ON SOLIDS CONCENTRATION BY CONCURRENT CENTRIFUGE AT 90% RECOVERY.

(Reprinted by permission from Vol. 38, No. 2, p. 253, Feb. 1966, J. Water Pollution Control Federation)

The machine centrate, at Yonkers, is returned to the pre-aeration tank for mixing with raw sewage. No operational problems were caused by this recycle of centrate. Polymeric flocculents were tested; they increased the solids capture from 76.2 to about 93 percent. Chemicals are not being used because of the added cost and because centrate solids resettle in the primary clarifiers.

The total capital cost of the Yonkers' centrifuge and the building in which it is contained was $141,900(127). Annual costs are about $15,500; the operating cost is about 39 percent of this total. Sixty man-hours per week are assigned to the centrifuge. On a per ton basis the annual cost for centrifuge thickening is about $3 to $4 per ton because nearly 5,000 tons of sludge are barged to the ocean(72).

In 1961, The Dow Chemical Company evaluated centrifuge thickening of waste activated sludge produced from treating an integrated chemical plant wastewater(117). A solid-bowl machine thickened a feed from 2.5 to 6 percent. Machine parameters used were: average speed, 2300 rpm and pool depth, 2-1/8 inches. About 2 pounds of dry solids were produced per minute with a solids capture of 85 to 97 percent.

Summary - Centrifugation has definitely proven its ability to thicken a variety of wastewater sludges. With recent improvements in machine design, this process will become more popular. The annual operating cost is about $3 to $8 per ton, if chemicals are not required. The thickening of waste activated sludge by itself can probably be done with less cost in air flotation units, unless chemicals are required in the flotation unit operation but not the centrifuge. Chemicals could add $3 to $10 per ton to the operating cost of centrifuges.

The Yonkers operation appears to be a good application for the use of centrifuges to thicken digested sludge in conjunction with gravity thickening of raw primary sludge. At one location, the centrifuge used to dewater digested sludge is also used to thicken the raw sludge fed to the digester. Unless space and odors are a problem, however, raw primary and mixed sludges are most efficiently thickened in gravity settling tanks.

Centrifuges are a compact, simple, flexible, self-contained unit, and the capital cost is relatively low. They have the disadvantages of high maintenance and power costs and often a poor, solids-capture efficiency if chemicals are not used. Overall, the advantages outweigh the disadvantages, so they will be installed with increasing frequency. The dewatering chapter of this report contains a detailed discussion of centrifuges.

## 6. SLUDGE BLENDING

Most physical, chemical, and biological processes proceed more efficiently if the input material is of a uniform nature. This is true for typical waste treatment processes such as sludge thickening, sludge dewatering, sludge digestion, and sludge incineration. For this reason, blending becomes important at secondary treatment plants where two vastly different sludges are produced.

Blending may be simply achieved by recycling secondary sludges to primary clarifiers where the sludge resettles and is mixed with the primary wastewater solids. The mixing of different sludges in pipelines, feeding thickening tanks allows adequate blending particularly if the sludges are dilute. The sludge collectors and picket thickening devices further aid blending in gravity tanks. Digesters designed for complete mixing can uniformly blend the contained sludges.

Blending sludges to produce a uniform mixture is particularly important ahead of incinerators, mechanical dewatering equipment, and digesters having inefficient mixing systems. For example, processing a uniform sludge can significantly improve the economics and performance of vacuum filter operations. In situations where sludge characteristics vary, the usual operating procedure is to overdose the sludge with chemicals to insure satisfactory mechanical performance. Overdosing wastes chemicals. But, improperly conditioned sludge leads to low filter yields, high cake moisture, and excessive labor for supervision of filtration and maintenance of blinded filter media. A blended sludge permits the more efficient use of chemicals because it has a more uniform and predictable flocculent demand than unblended material.

Different sludges are usually blended before the mechanical dewatering, incineration, and digestion steps by air agitation or by vigorous mechanical mixing in storage tanks. Both methods have the disadvantage of liberating entrained gases from the sludge. These gases cause air pollution problems unless the tanks are covered and the gases are exhausted to a deodorization process. Air agitation could be the superior technique because it freshens sludge and there is abundant data which shows that freshening lowers filtration costs. Overly vigorous mixing must be avoided otherwise the sludges to be dewatered may be deflocculated; this in turn increases the cost of dewatering.

Design engineers should be aware of the importance of thoroughly blending sludges ahead of certain unit processes.

# 7. SLUDGE DIGESTION

## A. Anaerobic Digestion

### General

Design engineers do not express uniform opinions on the merits of anaerobic digestion. Because there are significant advantages and disadvantages to this process, its application should be thoroughly evaluated for each individual situation.

Digestion essentially competes with incineration and mechanical dewatering. If a sludge is to be incinerated, it appears reasonable to eliminate expensive digesters because digestion lowers the Btu value of each pound of solids. At small wastewater treatment plants, landfilling of mechanically dewatered raw sludge is often feasible. It may be competitive with digestion followed by lagooning or liquid land disposal of the end product.

The major justification for digestion is that it stabilizes raw sludge and makes it more acceptable for final disposal. Other arguments for digestion, such as volume reduction and the production of usable gas, are insignificant in comparison with the conversion of noxious raw material, including fats, proteins, cellulose, and pathogenic organisms, into a more acceptable product. This important justification has made anaerobic digestion the most common method of processing organic sludges (53). There is a trend to systems designed around raw sludge handling but digestion will continue to be popular, particularly at small sewage treatment plants and in large coastal cities; digestion permits inexpensive land and ocean disposal at these locations.

The development of high rate digestion brought about significantly improved process economics. However, digester operating problems continue to plague most waste treatment plants, so additional process improvements are desirable. This chapter discusses anaerobic digestion from the standpoint of how it affects ultimate sludge disposal.

Theory and Objectives - Anaerobic digestion can be defined as the decomposition of organic matter in the absence of free oxygen. The decomposition is accompanied by gasification, liquefaction, stabilization, colloidal structure breakdown, and release of moisture(7). Digestion occurs in a mixed culture of microorganisms where particular species are most active in different stages such as acidification and gasification. In the digestion process, decomposition is not complete; the products of intermediate metabolism include organic acids, ammonia, methane, hydrogen sulfide, carbon dioxide, and carbonates. A 60 to 75 percent reduction in volatile solids is commonly achieved by anaerobic digestion, depending on the initial volatile solids content of the sludge.

The objectives of anaerobic digestion have been defined by various people to include the following:

1. Nuisance prevention by decomposing organic solids to a more acceptable stable form.
2. Sludge volume reduction by converting organic solids to gases and liquid.
3. Volume reduction by concentrating the remaining solids into a dense sludge.
4. Sludge storage to accommodate fluctuations in wastewater flows and to permit flexibility in subsequent dewatering operations.
5. Homogenizing sludge solids to facilitate subsequent handling steps.
6. Production of useful by-products such as gas and soil conditioner.
7. Reduction of pathogenic organisms.
8. Production of more easily dewatered solids.

Not all of these objectives are met in an individual anaerobic digestion system. For example, sludge concentration and the production of a more easily dewatered material are frequently not accomplished. "Bound" water in the sludge is often not released when the microorganisms attack and break down the complex molecular structure of the solids. High-rate digested sludge, having much entrained gas, is particularly resistant to solid-liquid separation.

Design Parameters and Operations - Anaerobic digestion is influenced by the following factors: (1) nature of sludge solids and their volatile content, (2) detention period in the digester, (3) temperature, (4) degree of digester mixing, (5) concentration of the feed sludge, (6) chemical additives, and (7) solids loading rate. These parameters affect ultimate sludge disposal processes in that a well-designed and operated digester produces a material that can be handled more easily and cheaply. A well-digested sludge has a low content (40 to 50%) of volatile material and dewaters reasonably well on sand beds or in mechanical equipment.

Since anaerobic digestion is a biological process, it is obvious that toxic materials in large quantities should be excluded from the digester. Examples of potentially toxic materials are heavy metals and cyanide. High concentrations of floating material such as skimmings, and industrial greases, and oils can be troublesome if the material in the digester is not completely mixed during the digestion process. Scum layers formed by low-specific-gravity solids can inhibit digestion and the free discharge of gas.

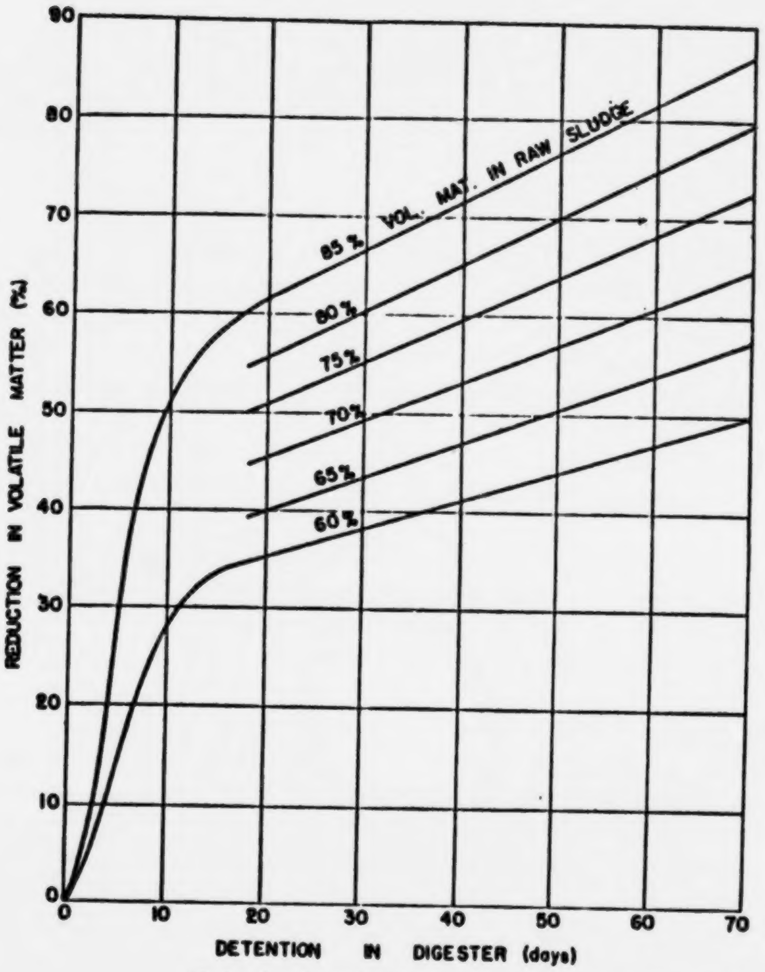
Generally, the higher the sludge volatile content is, the more efficient digestion becomes. Because digesters are designed on the basis of volatile pounds per cubic foot, this factor will influence the digester capacity.

A factor used to judge the quality of digested sludge is its volatile solids content. The percent of volatile solids remaining in the digested sludge is a function of the detention time in the digester(136). Figure 7.I illustrates two facts: (1) as the length of time allowed for decomposing raw sludge increases, the reduction in volatile matter increases and (2) larger percentage reductions in volatiles occur in raw sludges having higher initial volatile concentrations(11).

The rate of sludge digestion varies greatly with temperature; low temperatures result in low digestion rates. Figure 7.II shows the effect of temperature on the time required to reduce volatile solids in raw sludge to a desirable 40 to 45 percent range(11). Garber determined that temperature also affects other sludge characteristics(140). He evaluated sludge digestion at 85°F, 100°F, and 120°F. As expected, different microorganisms predominated at each temperature. However, other changes were noted at 120°F that affected sludge dewatering and disposal: (1) the average particle size was larger, (2) the proteinaceous material was more completely digested, and (3) the sludge had less total nitrogen, and the nitrogen present was in a different form. In addition, the methane content of the digester gas was higher at 120°F than 85°F.

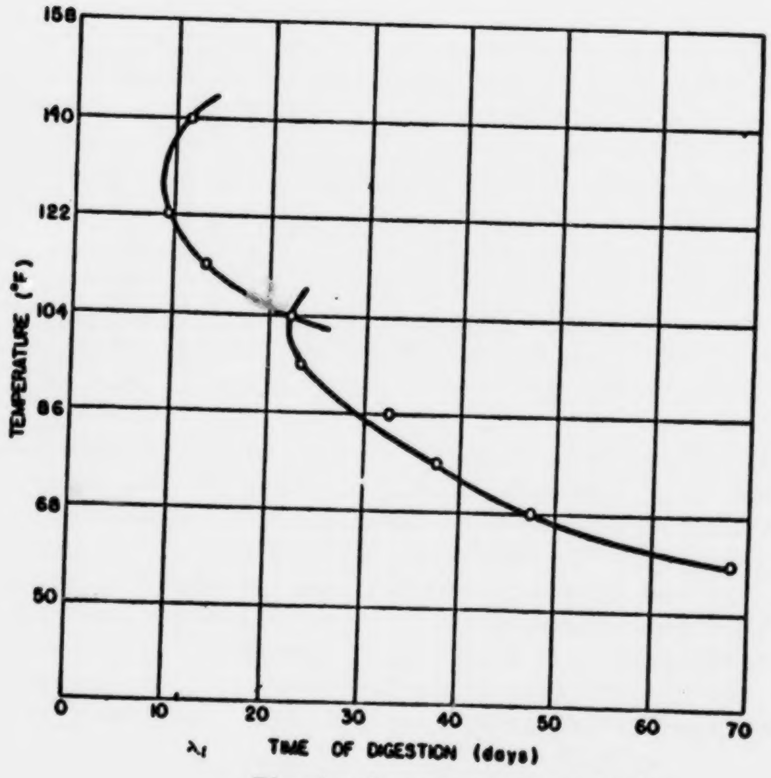
Digester contents should be well mixed, especially for high-rate digestion. Adequate mixing keeps microorganisms functioning at peak efficiency because they are in continuous contact with their food supply. In addition, mixing keeps the concentration of biological end products uniform and prevents scum accumulation. Mixing is done mechanically or by gas recirculation. About four techniques are available for each basic type of mixing; most people agree that all are technically satisfactory. Gas mixing has an operational advantage; it minimizes specialized equipment requirements.

Figure 7.I



Reduction in volatile matter for various sludges and digestion times.

Figure 7.II



Digestion time-temperature relationship.

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In general, attempts are made to digest as thick a raw sludge as possible. A maximum feed concentration is considered desirable because: (1) it conserves heat due to the minimum amount of water present, (2) it prevents dilution of the digester buffering capacity, (3) it encourages microorganism efficiency because their food supply is concentrated, (4) it increases detention periods, (5) it minimizes the supernatant volume returned to other treatment plant processes, and (6) it promotes the efficiency of subsequent dewatering steps. There is, however, a sludge concentration limit for satisfactory digestion. Viscosity and biological limitations are thought to occur at approximately the following maximum desirable concentrations (assuming good grit removal):

|  |  |  |
|---|---|---|
| 1. | Raw primary sludge | 10-16% |
| 2. | Raw primary + biofilter sludge | 8% |
| 3. | Raw primary + waste activated sludge | 6% |

Chemicals are usually added to sludge digestion tanks when there are operational problems. Historically, lime has been used when digestion is poor and acid conditions exist. Each digester may have its own critical pH which often is just 6.5 to 7.0. A recent innovation involving chemicals is the addition of anionic or cationic polyelectrolytes to digesters to improve supernatant quality. These organic materials are added as flocculents to sludge transfer lines between primary and secondary digesters. Flocculation of the solids promotes liquid separation in the secondary digesters.

The digester solids loading rate is an important parameter affecting unit performance. The microorganisms in a digester are relatively easy to upset, so they must be "fed" at acceptable rates. An optimum procedure would be a low uniform rate of sludge addition.

Increasing the loading rates of digesters and decreasing the detention time of the sludge -- a technique referred to as high-rate digestion -- represents a recent advance in solids handling and disposal techniques. The following loading and design criteria reveal why high-rate digestion has been accepted so enthusiastically (157, 38, 154):

1. Solids loading (pounds volatile solids/cu. ft./day)

| Standard rate | High rate |
|---|---|
| 0.04 to 0.1 | 0.15 to 0.40 |

2. Design criteria (cu. ft. of digester space/capita)

| | Standard rate | High rate |
|---|---|---|
| a) primary sludge | 2 to 3 | 1-1/3 to 2 |
| b) primary sludge + biofilter sludge | 4 to 5 | 2-2/3 to 3-1/3 |
| c) primary sludge + activated sludge | 4 to 6 | 2-2/3 to 4 |

3. Digestion period required (days)

| Standard rate | High rate |
|---|---|
| 39 (avg.) | 14.5 (avg. from actual plant data) |

Ten days is considered a practical minimum detention period for high-rate digestion, 6 days a theoretical minimum(153). Adequate mixing is the key to successful high-rate digestion because the digester volume is fully used for biological activity. Good contact of microorganisms and feed solids occurs. The homogenization of sludge, grease, and grit reduces build-up of unwanted scum and deposition of grit. The Densludge Digestion System developed at New York carries the process further, providing, in addition to continuous effective mixing, the following features(47):

1. Thickening of the digested feed sludge.
2. Feeding of the sludge on a substantially continuous basis.
3. Degritting of the sludge to a point where no grit settles out in the digester to occupy valuable space.

Degritting is done in hydrocyclone units (see the Grit Section of this report) and thickening, in gravity sedimentation tanks. The Densludge process usually has no supernatant liquor because the solid-liquid separation is accomplished in the thickening tanks.

Certain layout and structural features affect the performance of anaerobic sludge digestion. Two-stage digestion was considered an important advancement in the art. In the first stage, at least two-thirds of the decomposition occurs with an accompanying high gas production. Biological activity is too intense to permit solid-liquid separation with subsequent compaction of the digested sludge. These steps must, therefore, be accomplished in a second tank (stage). Heating and mixing facilities are often not incorporated in the second stage, on the assumption that they may hinder separation and compaction.

Unfortunately, high-rate digested sludge resists compaction and effective separation of liquids. As a result, the supernatant liquor has a high concentration of solids. This situation usually requires either: (1) removal of the supernatant liquid as thickener overflow before digestion, as recommended by the Densludge proponents(22), or (2) elutriation-thickening of the digested sludge before dewatering. Few investigators have explored the difference in dewatering characteristics between standard rate and high-rate digested sludges. MacLaren and others caution that the end-product of high-rate digestion may be difficult to dewater(53).

Digestion tanks should be designed so that they can be easily emptied to remove deposited grit or to make mechanical repairs(70). Some recent digester designs have incorporated hopper bottoms with flushing nozzles to facilitate the removal of grit without the need to use sludge as a carrier.

Facilities to use digester gas are often designed into waste treatment plants. The methane fuel value is commonly used to heat buildings, including the digester, and for plant power production(7). If the hydrogen sulfide concentration is high, the gas must be scrubbed The gas is also used to mix the contents of the digester.

In general, digestion tanks should be designed and operated for optimum liquefaction and gasification while converting the sludge to a form acceptable for disposal. Variations in ultimate disposal techniques, however, may dictate differences in design and operational procedures(157).

Performance - Much of the recent digester performance data compares high-rate and standard-rate digestion. Suhr and Brown made interesting comparisons at two Westchester County, New York, sewage treatment plants(147). Their data showed the following:

| | High Rate (Yonkers Joint Plant) | Standard Rate (New Rochelle) |
|---|---|---|
| Design capacity | 0.4 cu.ft./capita | 3.0+ cu.ft./capita |
| Digestion period | 16 days | 30 days |
| Volatile solids reduction | 64.5% | 65.9% |
| Digested sludge solids | 3.5 to 4% | 6 to 9% |

As the data indicates, high-rate digestion can produce the same volatile solids reduction as standard rate with much smaller digester capacity. However, the water does not separate as easily from the high-rate sludge as it does the standard rate. The Yonkers plant eventually added a centrifuge to thicken high-rate sludge prior to barging.

Rankin also compared high-rate with standard rate digestion performance(22):

| Detention Time (Days) | Volatile Solids Reduction (%) | |
|---|---|---|
| | High Rate (74.5% Volatile Sludge) | Standard Rate (75.0% Volatile Sludge) |
| 10 | 54.5 | - |
| 15 | 57.0 | 49.0 |
| 20 | 59.0 | 51.0 |
| 25 | - | 53.0 |
| 30 | - | 55.0 |
| 40 | - | 59.0 |

Standard-rate digestion required twice as long to reach 59 percent volatile solids reduction as the high-rate did.

Torpey (a pioneer in high-rate digestion and other processes) determined at New York that high-rate digestion could be done in 25 percent of the digester capacity normally required with conventional digestion(142). For 56.9 percent volatile matter reduction, this meant 0.5 cubic feet of digester capacity per capita rather than 2.1 cubic feet and 31 days detention rather than 54 days. Pre-thickening of modified aerated sludge to 10.2 percent removed the water normally separated as supernatant liquid in conventional units. Thickening followed by digestion in a single high-rate digester resulted in a digested sludge volume equal to that produced by four standard-rate digesters.

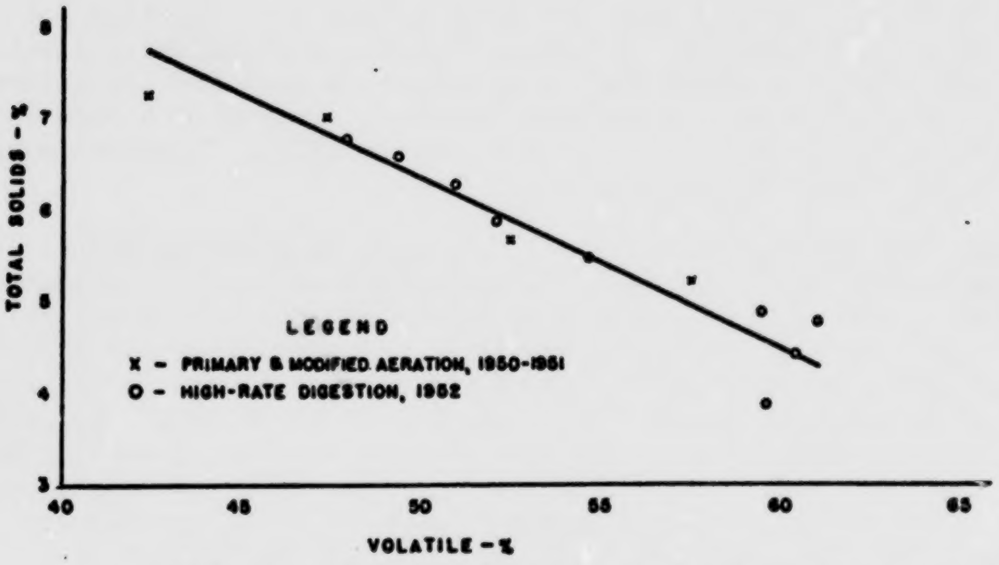
Whichever digestion process is used the concentration of digested sludge is (as shown in Figure 7.III) a function of its volatile content. The data represent similar volumes of the two sludges. The 1950-1951 data in Figure 7.III represents standard rate digestion(142).

Garber reported some very interesting data on high temperature digestion at the Los Angeles Hyperion Sewage Treatment Plant(140). As mentioned in the design parameters portion of this chapter, Garber investigated temperatures of 85°F, 100°F, and 120°F to produce a sludge more conducive to subsequent dewatering. The study showed little change in sludge characteristics between 85°F and 100°F. In either case the material was well digested but difficult to elutriate and vacuum filter. Supernatant separation was adequate only after very long detention periods. An attempt was made to thicken a 4-percent digested, elutriated sludge in one digestion tank, but after 25 days, the resulting 7 percent sludge could not be vacuum filtered.

Operations carried out at 120°F, however, resulted in significant improvements in sludge handling characteristics. First, there was good solid-liquid separation in the secondary digester which, in turn, improved vacuum filtration. This could improve overall treatment plant performance where supernatant liquid is returned to other plant processes. The solids concentration of the primary digested sludge increased from about 3.64 to 4.85 percent. Second, the improvement in vacuum filtration performance was unprecedented. The average filter yield increased from 1.7 to 6.3 pounds per square foot per hour. At the same time the ferric chloride flocculent demand was reduced from 6.5 to 3.4 percent. It was suggested that this improvement was due in part to less sludge "fines" (small particles) and the less gelatinous nature of the solids. Vacuum filter media plugging became less of a problem. A wet screen analysis showed that the percentage of particles passing a 200 mesh screen decreased from 80 to 65 percent.

The thermophilic (120°F) cultures were established in 30 days with seeding; once established the culture was quite stable and resistant to upsets. Gas produced from high temperature digestion had a higher-than-normal methane content; the protein in the sludge was more completely digested; and the sludge nitrogen content was less than normal. Doubling the solids loading of the digester had little effect except to reduce the gas production and volatile solids reduction a small amount.

Figure 7.III



**Relation of concentration of digested sludge to volatile content; primary and modified aeration sludge.**

(Reprinted by permission from Vol. 26, No. 4, p. 485, April 1954, J. Water Pollution Control Federation)

The problem of poor solid-liquid separation of anaerobically digested sludge was discussed by Steffen wnd Lemen in relation to meat packing wastes(144). At Albert Lea, Minnesota, a 20-inch vacuum is applied to remove entrained gases from digester liquor prior to separation of solids and liquid. This technique was successful and allowed a 390 percent increase in the digester loading because the separated solids are returned to the digester as seed. A moderate dose of cationic polyelectrolyte further increased the solid-liquid separation and resultant digester efficiency(193).

Economics - Digesters are expensive, about \$2.00 to \$2.50 per cubic foot(initial capital cost)but in many instances they are easily justified because they convert obnoxious raw sludge to a form suitable for disposal by relatively inexpensive methods. For example, most small sewage-treatment plants digest sludge because it permits sand-bed drying, lagooning or liquid land disposal. Most large coastal cities digest sludge because nuisance problems associated with ocean disposal are minimized. High-rate digestion systems have significantly improved the economics of this process for moderate to large facilities, but small plants usually are still designed on a standard rate basis because of the need for storage through winter months and other factors.

Any evaluation of competitive sludge handling processes should consider all factors involved in the waste treatment system. On this basis, digestion has certain disadvantages because it often results in a poor-quality supernatant liquor which causes problems when returned to other treatment units; it generates sludge "fines" that increase dewatering costs; and it probably is the major operational headache at most sewage treatment plants. A dollar and cents value can be attached to these digestion problems.

Some specific case histories of favorable digestion economics have been reported in the literature. Lynam and co-workers discussed the cost of new digestion systems at the Chicago Sanitary District(158). Using a 3.5 percent sludge, Chicago's cost of handling activated sludge by digestion and lagooning is \$22 per ton. Because sludges of other concentrations thicken and digest differently, their disposal costs naturally vary a great deal as shown in the following summary:

Total Solids in Feed

| | 2% | 3% | 4% | 5% | 6% | 8% |
|---|---|---|---|---|---|---|
| Feed tons per year | 17,820 | 26,800 | 35,850 | 45,000 | 54,000 | 72,400 |
| Lagoon area in acres | 108 | 162 | 216 | 271 | 325 | 435 |
| Total annual cost per ton | $32.32 | $24.03 | $20.06 | $17.51 | $15.89 | $13.77 |

The figures include capital and operating costs for sludge thickening by air flotation, digestion, pumping, and lagooning. Sludge thickening and digestion accounts for about 53 percent of total annual cost. Capital costs are based on 40-year amortization at 4% interest.

A comparison of the costs of high-rate and standard rate digestion systems in two cities has been reported by Westchester County, New York(147). The capital cost at Yonkers for high-rate digesters, two thickening tanks, and two storage tanks totaled $2.18 per capita. At New Rochelle, the capital cost of four standard-rate digesters was $5.86 per capita.

Estrada summarized actual cost differences between high-rate and standard-rate digestion systems. He stated that considerable savings are possible with high-rate designs due to the smaller size and decreased operational problems(154).

MacLaren estimated the cost in Canada for anaerobic sludge digestion using the following criteria: (1) raw sludge volatiles of 70 percent, (2) 30 days detention time, and (3) volatiles in the digested sludge of 45 percent(53). For cities between 1,000 and 100,000 population, annual capital charges are $9 to $14 per ton; operating costs are $2 to $4 per ton of sludge treated. The total annual cost for digestion alone is $11 to $18 per ton.

A general review of the literature indicated the cost of anaerobic digestion by itself should be $5 to $18 per ton. Total overall sludge handling costs for digestion and raw sludge systems are discussed further in the Economics chapter of this report.

Summary - In the majority of sewage treatment plants designed in the past, anaerobic digestion has been included as a primary part of sludge handling and disposal. The major justification for this popularity is the fact that nuisance-producing materials are made amenable to further disposal steps(157). Digestion stabilizes organic solids; odors are reduced; grease and other flotables can be assimilated and digested; and pathogenic organisms seem to die within 7 to 10 days of the start of digestion(17, 336).

The two other most frequently mentioned reasons for anaerobic digestion are gas production and sludge volume reduction. However, many local utility rates are so low that it is uneconomical to install equipment to develop power from the digester gas(152). Alternately, gas production may be sold to local industries as is being done at some West Coast sewage treatment plants(150). Volume reduction has been over-emphasized because, except for that resulting from gas production, it occurs only because of the formation of supernatant liquid. Supernatant production is one of the many disadvantages of digestion. It imposes a high B.O.D. and solids load on other treatment plant processes and the effluent receiving water. Most engineers do not make allowances for recycled supernatant liquid when they design clarifiers and biological units. These units are, therefore, often exposed to a build-up of the fine supernatant solids. As a result, treatment plant costs are higher than expected and overall treatment efficiencies lower.

In addition to supernatant production, the other major disadvantages of anaerobic digestion are: (1) the loss of nitrogen to receiving streams, (2) the cost, (3) the creation of many operational problems, and (4) the complication of sludge dewatering steps.

Nitrogen and phosphates remain in the supernatant liquid, eventually fertilizing the receiving water. This ever-increasing fertilization is a major problem in the water pollution control field. Where sludge is dried and sold as fertilizer, the decreased nitrogen content reduces the value of the material. Digestion tanks are big, expensive, and do not represent ultimate disposal. For these reasons they are often omitted from the designs of many wastewater treatment plants.

In regard to operational problems, digestion (and digesters) are usually the operator's biggest headache, they require a lot of attention. For example: digesters get "sick"; they foam; they require liming; grit removal is a major operation; gas production falls off; odor problems arise because the sludge is incompletely digested; scum blankets form; mechanical mixers corrode; and sludge does not thicken.

Digested sludge is often dewatered mechanically. This step may be preceded by elutriation to remove the undesirable by-products of digestion that interfere with efficient dewatering (see the Elutriation chapter). The resultant elutriate which is recycled to the primary sedimentation basins, often contains a high concentration of fine solids. These solids present the same problem as supernatant solids. The two together (elutriate and supernatant solids) create a major B.O.D. and solids load onto the other unit processes. Some investigators claim that digestion alters the solids water binding characteristics and makes dewatering easier and less costly. On the other hand, digestion increases the concentration of fine particles and the specific resistance to filtration(13)(see the Vacuum Filtration chapter for typical data).

In summary, the ultimate sludge disposal technique plus the size and location of the waste treatment plant greatly influence the decision of whether to use anaerobic digestion. Certainly small plants and coastal plants will continue to digest because it prepares the organic sludges for cheap final disposal. Many plants not in these two categories must weigh local conditions and the many technical factors involved with digestion. Mechanical dewatering and incineration of raw sludge is becoming more popular, even at small plants, in part due to design improvements. However, odor control is a problem when handling raw sludge; this fact again emphasizes the major justification for digestion -- nuisance prevention by sludge stabilization. High-rate digestion has improved the economics of digestion considerably but it introduced other problems such as the production of poor quality supernatant liquid and a sludge that may be difficult to dewater.

Because anaerobic digestion will continue to be the most common method of processing sludge for many years, new research is needed to make the process more efficient. Additional analytical tools would be desirable to control the process more accurately. Measurements such as pH, volatile acids, bicarbonate alkalinity, and gas production indicate the general state of digestion, but may not give warning of failure in the system. Frequent analyses and scientific interpretation of the basic data may allow an early prediction of trouble, but better techniques are still needed. Continuous analyses for methane, carbon dioxide, hydrogen sulfide, and ammonia by gas chromatography could aid in controlling digestion if the data were interpreted scientifically in conjunction with the other basic data. Other measurable parameters have been suggested; these include dioxyribonucleic acid (DNA)(159), viscosity, and the protein-carbohydrate-fat ratio. A simple test to indicate needed operational changes before a digester is fouled with poorly digested sludge would be extremely valuable.

The design of a digestion system that is more efficient and stable would be a great improvement. High-rate digestion with its related vigorous-uniform mixing and sometimes concentrated feed is an improvement but further improvements are desirable. A better definition of loading criteria including frequency of digester feed, would be useful. Perhaps different biological cultures in different digestion stages should be developed. Addition of enzymes and biocatalysts has been briefly explored but not in sufficient detail. The addition of nutrients to the digester has been suggested to increase the tank efficiency(157). Spohr examined the use of an electric current to keep microorganisms in the low growth phase as a means of more efficient digestion(146). Garber and others concluded that the advantages of thermophilic digestion far outweighed the disadvantages and so it appears further research is justified(140).

Tailoring the anaerobic digestion process to produce a sludge which is easily dewatered in mechanical equipment or on sand drying beds should be considered. This may require operating at uncommon temperatures and detention periods as well as placing the analytical emphasis on solids characterization.

Because digester supernatant liquid often reduces overall treatment plant efficiences, improved techniques for its handling are desirable. Pre-thickening of raw sludge (or raw sludge mixed with digested sludge) ahead of the digester may be the most acceptable technique because the supernatant liquor would be completely replaced by less troublesome thickener overflow. Handling supernatant separately rather than returning it to other treatment plant processes can be done satisfactorily by a number of methods. Dewatering on sand drying beds, particularly after chemical conditioning, is an efficient method of dewatering prior to ultimate land disposal (see the Sand Bed Drying chapter). Supernatant liquid can be stabilized by aeration, copper sulfate, or chlorine and then discharged to lagoons or spread on land as a liquid fertilizer. Dewatering of supernatant liquor in centrifuges prior to land disposal has been successful. Treating supernatant with lime, separately or in combination with elutriation basin overflow, is an interesting possibility because a saleable fertilizer would result due to the nitrogen and phosphates in supernatant liquids.

Other miscellaneous improvements that would be beneficial to digestion operation include: (1) more efficient removal of the grit in digestion tanks, (2) tanks designed to facilitate cleaning, and (3) techniques for degasifying sludge (such as vacuum techniques) to allow increased solid-liquid separation in subsequent units.

Since the conversion to biodegradable (LAS-type) detergents, digester problems have reportedly increased. A number of sewage treatment plant operators believe these new detergents cause sludge to resist digestion at normal efficiencies. Research to investigate this situation is needed.

Without doubt, much more research in anaerobic digestion is justified. Heavy metals toxicity has been extensively studied; if the same amount of effort were directed at solving the problems discussed in the preceding paragraphs, the operation of treatment plants would be substantially improved.

## B. Aerobic Digestion

General - Aerobic digestion is not commonly practiced at sewage treatment plants. However, in recent years, due to a rapid increase of "extended aeration" treatment plants, aerobic digestion of sludges has been receiving increased attention.

The major advantage of aerobic digestion is that it produces a biologically stable end product suitable for subsequent treatment in a variety of processes. Volatile solids reductions similar to anaerobic digestion are possible with short detention periods.

Aerobic digestion followed by lagoons is often considered by industry to be the most suitable technique for solids disposal.

This section emphasizes aerobic digestion as it applies to a separate treatment unit after solids-liquid separation steps.

Theory - Aerobic digestion has been described as a process where microorganisms, "Obtain energy by auto-digestion of the cell protoplasm and the biologically degradable organic matter in the sludge cells is oxidized to carbon dioxide, water, and ammonia"(167). The ammonia is further converted to nitrates as aerobic digestion proceeds. After a while the oxygen uptake rate levels-off, and a final material is produced that consists of inorganics and volatile solids that resist further biological destruction. Loehr stated that oxidation in aerobic digestion systems includes the direct oxidation of biodegradable matter by organisms plus endogenous respiration or the oxidation of microbial cellular material(168). He concluded that endogenous respiration is the predominant metabolic reaction in aerobic digestion.

Parameters - Some parameters affecting the aerobic digestion process are: (1) rate of sludge oxidation, (2) sludge temperature, (3) system oxygen requirements, (4) sludge loading rate, (5) sludge age, and (6) sludge solids characteristics.

Barnhart reported that volatile solids in a variety of domestic and industrial sludges were substantially reduced after ten days aeration (164). Figure 7.IV shows that the volatile solids reductions for all sludges except the mixed pulp and paper waste were quite acceptable with increasing detention times.

Viraraghavan's laboratory studies using sewage sludge showed that an almost straight-line relationship existed between volatile solids

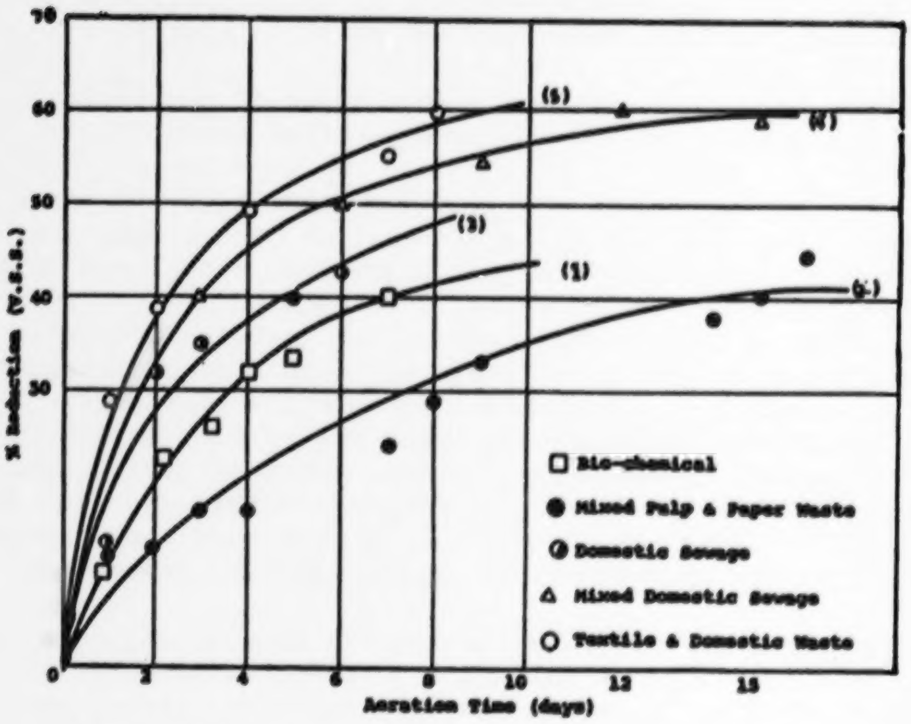


Figure 7.IV - *Solids reduction by aerobic digestion.*

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reduction and detention time up to 15 days. Figure 7.V reveals little further reduction of volatiles after 15 days(166).

The volatile solids reduction in aerobic digestion approaches a limit with increased detention periods; the exact limit depends on the characteristics of waste fed to the system. Substantial data from activated sludge systems indicates that a volatile solids reduction limit of 40 to 60 percent can be expected when treating domestic and industrial sludges(168).

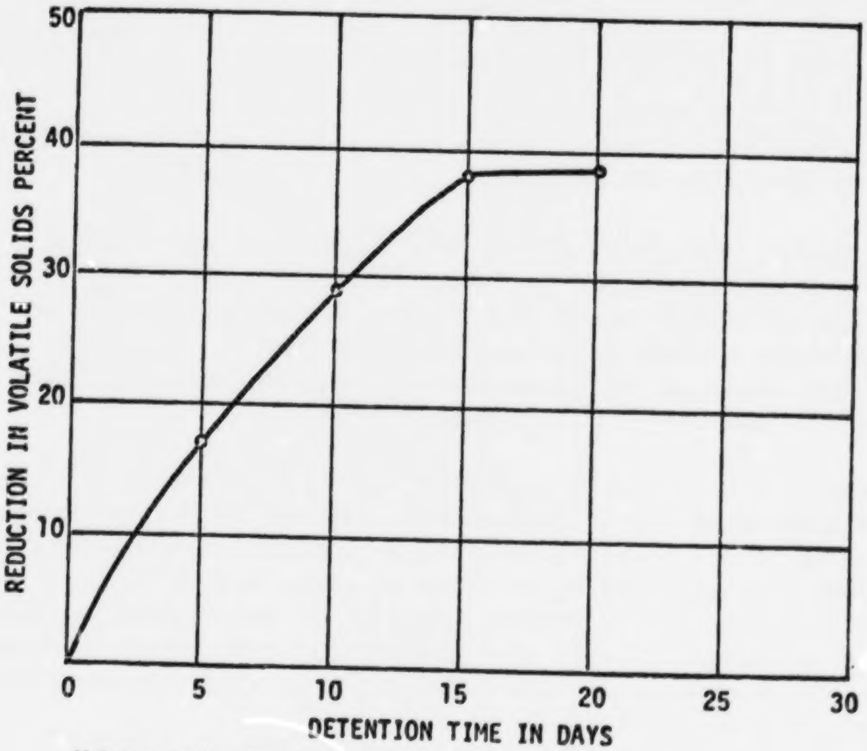
Laboratory research on aerobic digestion using a mixture of raw primary and waste activated sludge was sponsored by Walker Process. Figure 7.VI shows the effect of detention time and temperature on volatile solids reduction as determined by this study(167). Volatile solids reduction increases sharply as the detention time is extended to 12 days. Beyond that time only a moderate increase was noticed. The curves show increased removal with higher sludge temperature of from 15°C to 35°C.

In general, the data developed from the Walker Process studies revealed the following effects of temperature(167): (1) at a detention period of 60 days, temperature has no effect since digestion was complete at all temperatures, (2) a minor temperature effect was noticed at the very short detention period of 5 days, and (3) the 10 and 30 day detention periods were noticeably influenced by temperature. Higher temperatures produced greater volatile solids reductions.

The investigations of temperature by Reyes and Kruse have been reported by Leohr(168). After aerobic digestion for 20 days, they achieved sewage sludge volatile solids reductions of 25 to 35 percent at 8°C and 67 percent at 60°C. One report concluded that excessive sludge temperatures can be detrimental to subsequent handling steps. Aerobic digestion of primary sludge was reported to be more efficient at 35°C (mesophilic) than at 52°C (thermophilic)(168). Thermophilic oxidation produced a greater reduction in ether solubles than mesophilic, but the oxidized sludge did not settle and the sludge after drying had a fiberous character.

Loehr reported that sludge oxidation rates vary depending on the sludge microbial population, the characteristics of the raw waste, the sludge age, and the sludge temperature(168). Old sludges have been partially oxidized before aerobic digestion, therefore, the volatile solids reduction is less than that of fresh sludge. The

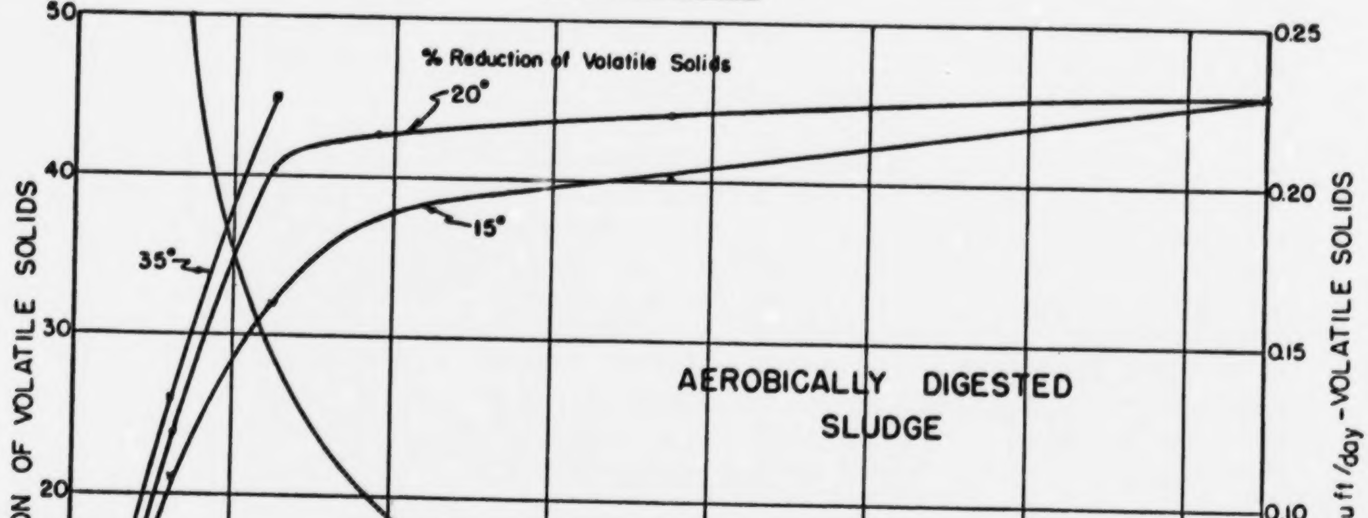
Figure 7.V



Volatile solids reduction—effect of detention time.

(Reprinted by permission Water and Wastes Engineering)

Figure 7.VI



(Reprinted by permission Walker Process Equipment, Inc.)

work of Burton and Malina on loading rates was also reviewed by Loehr(168). Their data revealed an increase in volatile solids reduction at higher loadings. Volatile solids were reduced 43 percent at a loading of 0.14 pounds volatile solids per day per cubic foot, and 34 percent at a loading of 0.10 pounds per day per cubic foot.

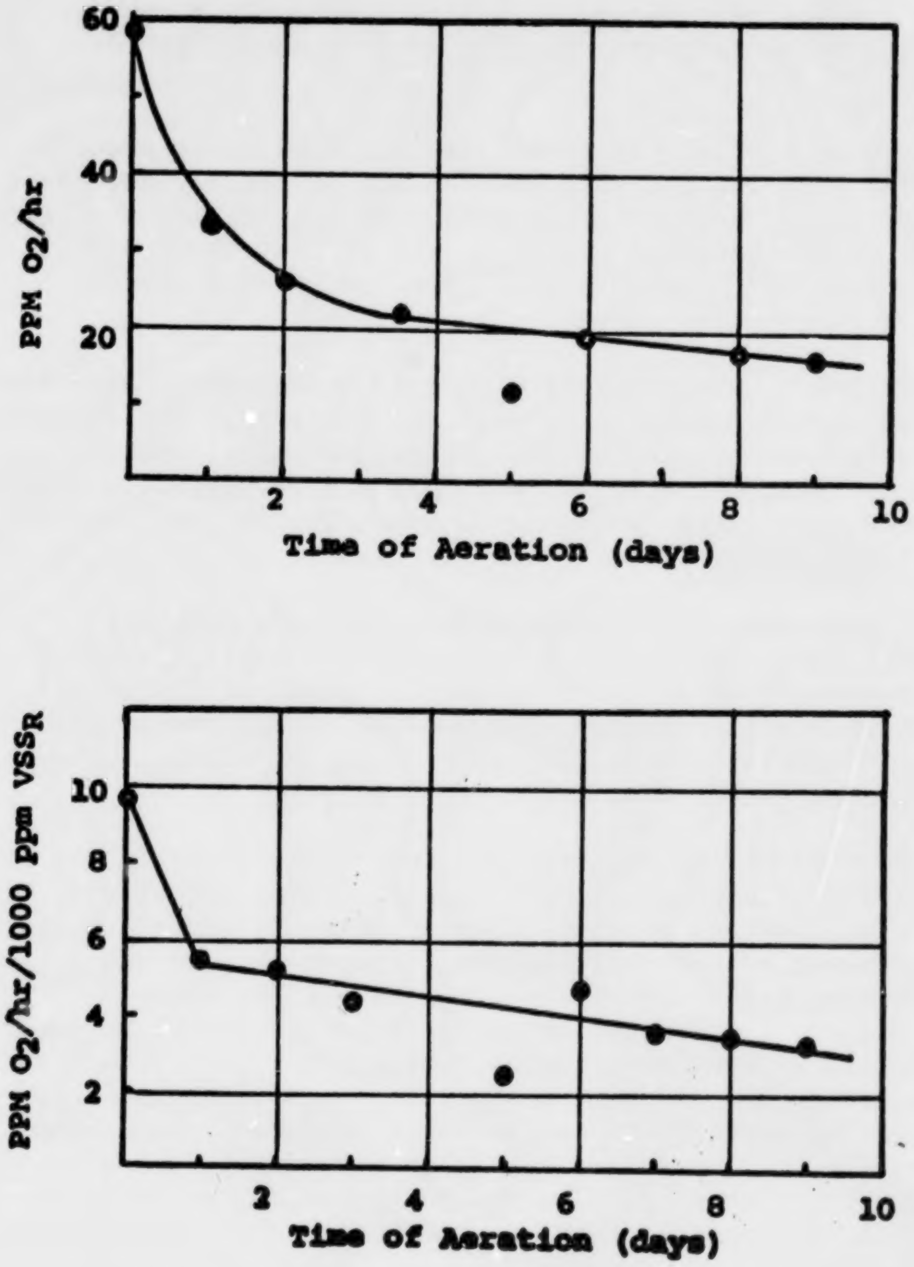
Figure 7.VII shows typical oxygen utilization curves for aerobic digestion(164). The initial rate is high but it rapidly decreases after the first day. Barnhart suggested that the utilization rate is a function of the material stored in the cell at the start of aerobic digestion(164). After 1 to 2 days the rate of oxygen utilization decreases very slowly.

One theory applied to small extended-aeration treatment plants was that prolonged aeration eventually oxidizes the sludge solids to carbon dioxide and water, and no net sludge accumulation occurs. But, it has been observed that 20 to 25 percent of the biological solids produced is relatively immune to bio-oxidation and, therefore, accumulates in the system(168).

Numerous investigations of aerobic, digested-sludge drainage characteristics have been made. In general, the data indicated that sludge aeration for at least 10 days is required for good drainage. After 5 days aeration, the drained sludge was of poorer quality than undigested sludge, but after 10 days aeration, the drained sludge was better than undigested sludge(161).

Design - Aerobic digestion has been applied mostly to various forms of activated sludge treatment, usually "total oxidation" or contact stabilization plants. However, aerobic digestion is suitable for many types of municipal and industrial wastewater sludges, including trickling filter humus as well as waste activated sludges. Information on design criteria is not abundant, but the technical literature contains figures that can be used as limits. Any design for an aerobic digestion system should include: an estimate of the quantity of sludge to be produced, the oxygen requirements, the unit detention time, the efficiency desired, and the solids loading rate(168). The following limits, relating to the above estimates were discussed in the literature:

Figure 7.VII



*Oxygen utilization during aerobic digestion.*

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Solids Loading Rates(167):

1. Primary sludge plus waste activated sludge
   0.20 pounds total suspended solids (T.S.S.) per capita per day.

2. Primary sludge plus trickling filter humus
   a) high rate filters 0.19 lbs. T.S.S./capita/day
   b) standard rate filters 0.17 lbs. T.S.S./capita/day

Air Requirement(167):

15-20 cfm per 1,000 cubic feet of digester capacity is adequate. The air supplied must keep the solids in suspension; this requirement may exceed the sludge oxidation requirement. Loehr recommended a liquid velocity in the aeration tank of 0.5 fps to keep all the biological solids in suspension(168). A dissolved oxygen concentration of 1 to 2 ppm should be maintained in the aerobic digestion tanks.

Power Requirement(167):

About 10 BHP (Brake Horse Power) per 10,000 population equivalent is an estimate of power required for aeration.

Detention Time(167):

1. Waste activated sludge only, after sludge thickening.
   10-15 days volumetric displacement time.
   If sludge temperatures are much less than 60°F, more capacity should be provided.

2. Primary sludge mixed with waste activated or trickling filter humus.
   20 days displacement time in moderate climates.

Two-stage digestion was evaluated and the conclusion was made that it offered no advantages over one-stage aerobic digestion.

Tank Design(167):

Aerobic digestion tanks are normally not covered or heated, therefore, they are much cheaper to construct than covered, insulated, and heated anaerobic digestion tanks. In fact, an aerobic digestion tank can be considered to be a large

> open aeration tank. Similar to conventional aeration tanks, the aerobic digesters may be designed for spiral roll or cross roll aeration using diffused air equipment. The system should have sufficient flexibility to allow sludge thickening by providing supernatant decanting facilities.

More detailed design considerations are discussed by Loehr(168). He made the very significant observation that in secondary waste treatment plants, the most economical sludge disposal system could be one where the primary and secondary sludge is handled separately. This could mean anaerobic digestion of primary sludge and aerobic digestion of waste activated sludge. Loehr reported that the oxygen supply should be increased almost nine times when aerobically digesting primary with activated sludge, as opposed to waste activated alone. This means a minimum air supply of 90 cfm per 1,000 cubic feet of aeration capacity. Sludge segregation should certainly be considered.

Loehr cautioned that the aerobic digester should be designed so the required degree of oxidation occurs during colder months(168). Because aerobic digestion tanks are normally not covered or heated, the minimum volatile solids reduction occurs in the winter.

Performance - One of the most important aerobic digestion case histories describes sewage sludge handling at the OSO plant in Corpus Christi, Texas(167). Waste activated sludge, formerly recycled to the primary sedimentation basins, upset many unit processes: the primary tanks were odorous and inefficient due to the high solids load; the aeration tanks were overloaded because sludge did not settle well in the primary tanks; anaerobic digestion capacity was limited due to the inclusion of waste activated sludge; and the sludge mechanical dewatering and drying processes were costly and odorous as a result of combining waste activated with primary sludge.

After substituting an aerobic digestion system for the waste activated sludge in place of recycling the following operating improvements were noted: (1) the efficiency of the primary tanks increased and less activated sludge solids were produced, (2) odors from primary sedimentation basins and thickening tanks were eliminated, (3) anaerobic digestion began operating smoothly on primary sludge alone, and (4) the sludge drying time was greatly reduced. The aerobic digester, operating with a 10 day detention period, produced a stable sludge that was used on the treatment plant lawns with no noticeable odor. Decanted supernatant liquor had an average B.O.D. of 10 ppm.

Dreier reviewed aerobic digestion performance at Batavia, Illinois(161, 167). This city aerobically digested a mixture of raw primary and waste activated sewage sludge prior to vacuum filtration. Sludge fed to the digester averaged 4.75 percent solids and that withdrawn for filtration, about 2.77 percent. The operation included sufficient air to maintain aerobic conditions and a decanting arrangement to thicken the sludge. Chemical costs per ton of solids filtered at Batavia increased slightly above the cost for undigested sludge, but the total economics of the system improved due to sludge volume and labor cost reductions.

The sanitary district at Rockford, Illinois, evaluated aerobic digestion of mixed primary and trickling filter humus(161, 167). After 30 days detention, the sludge was placed in a lagoon in an odor-free condition. Because anaerobic digesters were already in existence at Rockford, they considered the possibility of following anaerobic digestion with aerobic digestion to assure an odor-free lagoon operation.

Aerobically digested sewage sludge from a typical contact stabilization process treatment plant was reported to have the following characteristics(167):

| | |
|---|---|
| pH | 5.6 |
| Alkalinity | 283.0 ppm |
| Total solids conc. by decanting | 2.76% |
| Volatile solids reduction | 32.0% (48.8% volatiles initially) |
| Nitrate-nitrogen | 48.0 ppm |
| Ammonia nitrogen | 1.75 ppm |
| B.O.D. of the supernatant liquor | 16.0 ppm |
| ORP (oxidation Reduction Potential) | 740.0 MV |

Small "package plants" produce an aerobically digested sludge that is discharged to lagoons, sand drying beds, and receiving streams usually without causing nuisance problems. Many references indicated rapid dewatering on sand beds was achieved after the sludge had been digested for at least 10 days.

Carpenter and Blosser investigated aerobic digestion of waste activated papermill sludges (boardmill and deinking)(163).

They arrived at the following conclusions from their study:

1. Little volatile solids reduction occurs after 27 days digestion.

2. There is a small increase in volatile solids reduction with the addition of nitrogen and phosphorus to the sludge.

3. The rate of solids decomposition is doubled with a 10°C rise in the temperature.

4. System oxygen requirements are:

    a) before digestion, 9-12 ppm per hour per 1,000 ppm volatile solids
    b) after one day aerobic digestion, 4-7 ppm per hour per 1,000 ppm volatile solids
    c) after two days to completion, 2.5-6 ppm per hour per 1,000 ppm volatile solids.

5. Sludge aerated for long periods floated unless degasified by a slight vacuum.

6. Aerobically digested sludge did not dewater as well as raw sludge. Mechanical breakdown of the sludge floc may be responsible for the unsatisfactory dewatering characteristics.

Barnhart reported on the stabilization of thickened industrial sludges with prolonged aeration(164). He observed that subsequent solid-liquid separation steps such as thickening and vacuum filtration could proceed normally. The volatile solids reductions were similar to anerobic digestion so long as the temperatures exceeded 20°C. Below this point, solids reduction rates decreased rapidly. Other experimenters have agreed that low temperatures are not acceptable. With the proper temperature, 15 days detention time was acceptable in all cases studied.

Economics - Cost information for aerobic digestion systems is not plentiful because the process is relatively new. In general, however, the power cost for a treatment plant with large quantities of sludge, and therefore a need for large volumes of air, is a major disadvantage to the process. One engineer estimated that the horsepower requirement in a biological treatment plant would be doubled after adopting aerobic digestion. This is not a major concern for small treatment plants, but it certainly would be for a large facility.

When compared with anaerobic digestion, the capital cost for aerobic digestion is much lower because the tanks required are smaller and less costly to construct per cubic foot. Duquesne, Pennsylvania, for example, constructed an aerobic digestion facility at a cost significantly less than that possible with anaerobic digestion(160). They produce a stable odorless sludge after 14-days aeration of a gravity thickened material.

Summary - Many municipal and industrial wastewater treatment plants practice aerobic digestion. Technical data from these operations are not plentiful which, unfortunately, encourages the idea that aerobic digestion is a new, unproven technique for solids handling. But, aerobic digestion has some important advantages that justify attention by researchers and design engineers.

The advantages most often claimed for aerobic digestion are:

1. A humus-like, biologically stable end product is produced.

2. The stable end product has no odors, therefore, simple land disposal, such as in lagoons, is feasible.

3. When compared with anaerobic digestion and other schemes, capital costs for an aerobic system are low.

4. Aerobically digested sludge usually has good dewatering characteristics. When applied to sand drying beds, it drains well and redries quickly if rained upon.

5. Volatile solids reduction equal to anaerobic digestion is possible with aerobic systems.

6. Supernatant liquors from aerobic digestion have a lower B.O.D. than those from anaerobic digestion. Most tests indicated that B.O.D. would be less than 100 ppm. This advantage is important because the efficiency of many treatment plants is reduced as a result of recycling high B.O.D. supernatant liquors.

7. There are fewer operational problems with aerobic digestion than with the more complex anaerobic form because the system is more stable. As a result, less skillful labor can be used to operate the facility.

8. In comparison with anaerobic digestion, more of the sludge basic fertilizer values are recovered.

The major disadvantage associated with aerobic digestion is, as mentioned earlier, high power costs. This factor is responsible for the high operating costs in comparison with anaerobic digestion. At small waste treatment plants, the power costs may not be significant but they certainly would be at large plants. Some investigators have observed that aerobically digested sludge does not always settle well in subsequent thickening processes. This situation leads to a thickening tank decant having a high solids concentration.

Some sludges do not dewater easily by vacuum filtration after being digested aerobically(163). Two other minor disadvantages are the lack of methane gas production and the variable solids reduction efficiency with varying temperature changes.

Aerobic digestion may be particularly suitable for industrial sludge treatment and to sludge at small, activated-sludge plants. The industrial community apparently favors aerobic digestion because of the low capital investment and simple operation. In industry, mechanical aerators are often used in inexpensive open tanks followed by lagoons. While there is a difference in emphasis at municipal waste treatment plants as regards costs, it seems logical that aerobic digestion should be further evaluated, particularly for activated sludge facilities.

The experience at Corpus Christi is significant because a difficult problem was solved by handling secondary sludge separately from the primary sludge. Corpus Christi's problem was certainly not unique. Biological sludges often upset unit process operations and lower the overall treatment plant efficiency. Separating this sludge, as they did at Corpus Christi, and digesting it aerobically could be a good solution to a difficult problem. It permits more efficient and economical operation of primary sedimentation basins, anaerobic digestion tanks, and vacuum filters because the gelatinous biological sludge is removed from the system. Usually it is more economical to combine sludges prior to dewatering and disposal; but, where difficult sludges are encountered, separate treatment may be desirable.

Certainly more technical information on aerobic digestion is needed for a proper evaluation of the process. Acquiring additional data from existing systems would be a desirable first step. A considerable amount of new research in the process and in engineering design should be accomplished to improve existing technology. Very little information is currently available concerning loading rates, air requirements, rate of sludge oxidation, the effects of varying sludge characteristics, sludge amenability to subsequent handling and disposal steps,and cost-performance. Aerobic digestion will not be routinely included in sludge treatment evaluations by consulting engineers until more data is collected and disseminated.

## 8. ELUTRIATION

General - Elutriation can be defined as a washing operation which removes sludge constituents that interfere with thickening and dewatering processes. This unit operation is usually associated with vacuum filtration of digested sewage sludge. Elutriation reduces the flocculent demand of a sludge by improving the physical and biochemical quality of its solid and liquid components. In addition to reducing the chemical conditioning required prior to filtration, elutriation has also been proven to be a useful sludge thickening device at numerous sewage treatment plants. Other "secondary" applications of elutriation include washing-out toxic materials that inhibit sludge digestion or other biological processes, and the treatment of dirty digester supernatant liquor(177). Toxic materials should be removed from wastewater before discharge to a sewerage system but, if not, removal is possible by elutriation(65). Elutriation of digester supernatant liquor permits the capture of the solids and return of relatively clear supernatant liquor to primary sedimentation. The captured solids are stored and dewatered with the normal plant sludge(177).

Unfortunately, elutriation has not been a completely successful process at all locations. A major operational problem has developed in many plants due to poor solids capture in elutriation basins. The high concentration of fine solids in the recycled elutriate at these plants overloads other processes, thereby decreasing the overall plant efficiency.

This chapter discusses elutriation as part of the following subject headings: (1) sludge alteration, (2) process design and operation, (3) chemical reduction, (4) sludge thickening, (5) chemical aids, (6) economics, and (7) evaluation and summary of the process.

Sludge Alteration - Digestion substantially reduces the organic fraction in sludge solids while increasing biochemical products in the liquid fraction. Ammonium bicarbonate is the most important of these biochemical materials. It is quite common to have the bicarbonates present in the free water of raw sludge increased at least sixty times during digestion of the solids(177). The flocculent demand exerted by a sludge to be dewatered consists of a solids demand and a liquid demand best expressed by the alkalinity.

Genter defined elutriated sludge as one, "That has had the alkalinity of its biochemically fouled water reduced by dilution, sedimentation, and decantation in water of lower alkalinity"(21).

The washing operation removes excessive concentrations of soluble ammonium and other compounds while fractionating the solids allowing effective settling of coarse particles. It also washes out adsorbed gas bubbles developed in the digestion process. Fine and colloidal solids are not recovered. This is an advantage as regards vacuum filtration because fines consume a disapportionate amount of flocculents and clog the filter media. However, recycled elutriate having an excessive concentration of fines overloads other plant processes.

Elutriation produces a sludge with fairly uniform flocculating and dewatering characteristics. The bulk of the fines and alkalinity are removed along with the nitrogen compounds and entrained gas.

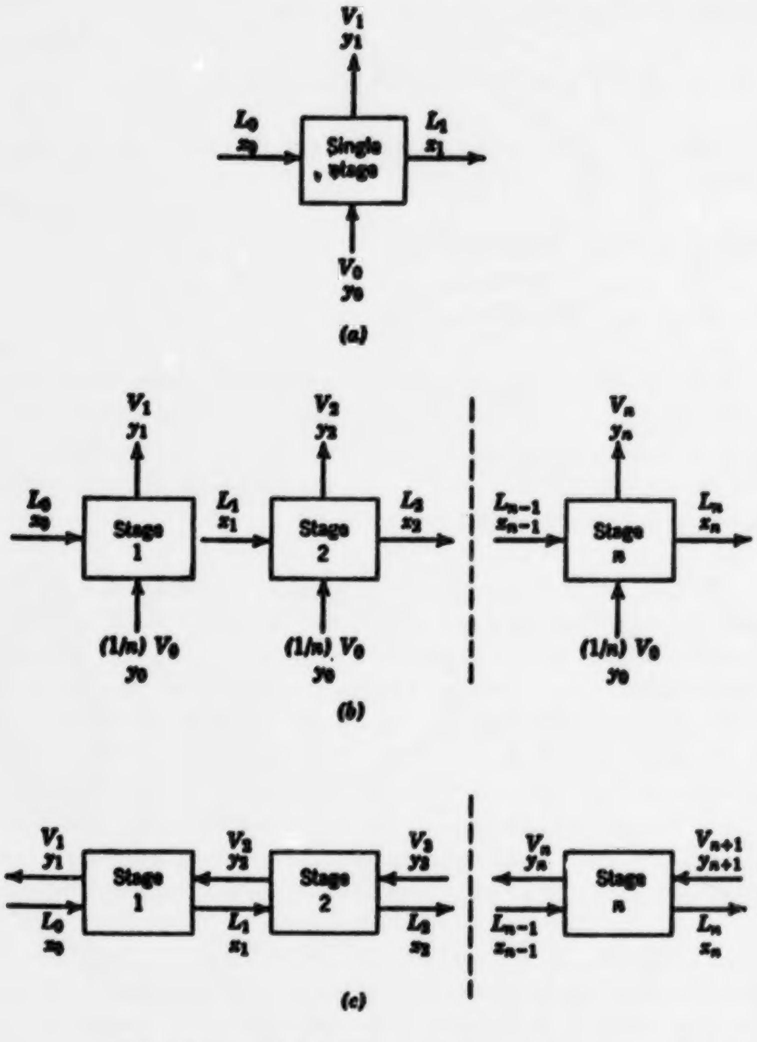
Process Design and Operation - Three common methods are used in elutriation operations(6). Figure 8.I illustrates the three procedures. The simplest method is the single stage with a single contact between the solids and liquids. Multistage cocurrent contact in one or more basins and multistage countercurrent contact are the other two methods commonly used. "Fresh water" is used in all stages of the cocurrent method. In a two-tank countercurrent system, fresh water is added only to the second stage washing. Second stage elutriate, or overhead water, provides the necessary wash in the first stage.

Elutriation operations may be continuous in one or more units, intermittent in one unit, or they may be operated on a batch basis. Progressive designers and operators usually reject fill-and-draw batch operations in wastewater treatment but this technique permits a high solids capture. After the basin is allowed for thorough subsidence and concentration of the washed solids. The relatively clear elutriate is then decanted and the sludge is pumped to the next solids handling process.

Wash water for elutriation may be plant effluent or water from nearby streams or wells. Ratios of wash water to sludge usually fall within the range of 2:1 to 12:1. The most common is 2:1 or 3:1. Factors affecting the operating ratio include sludge alkalinity, desired alkalinity of the washed sludge, wash water alkalinity, the sludge handling process following elutriation, and the availability of water and elutriation basin capacity.

Genter used the following equations to calculate the alkalinity, solid and liquid flocculent demand, of elutriated sludge(21):

Figure 8.I


$V_1$
$y_1$
$L_0$
$x_0$
Single stage
$L_1$
$x_1$
$V_0$
$y_0$
(a)
$V_1$
$y_1$
$V_2$
$y_2$
$V_n$
$y_n$
$L_0$
$x_0$
Stage 1
$L_1$
$x_1$
Stage 2
$L_2$
$x_2$
$L_{n-1}$
$x_{n-1}$
Stage n
$L_n$
$x_n$
(1/n) $V_0$
$y_0$
(b)
$V_1$
$y_1$
$V_2$
$y_2$
$V_3$
$y_3$
$V_n$
$y_n$
$V_{n+1}$
$y_{n+1}$
$L_0$
$x_0$
$L_1$
$x_1$
$L_2$
$x_2$
$L_{n-1}$
$x_{n-1}$
$L_n$
$x_n$
(c)

**Flow diagrams illustrating various arrangements employed in dispersed-contact leaching operations. (a) Single contact. (b) Multistage cocurrent contact. (c) Multistage countercurrent contact.**

(Reprinted by permission from Unit Operations of Sanitary Engineering, by L. G. Rich, Copyright 1961, New York, John Wiley and Sons, Inc.)

(1) $E = \frac{D + RW}{R + 1}$ for single-state elutriation,

(2) $E = \frac{D + W \ [(R+1)^n - 1]}{(R+1)^n}$ for n-stage elutriation, and

(3) $E = \frac{D + (W)\ (R^{2+R})}{R^2 + R + 1}$ for countercurrent elutriation in two mixing and settling tanks.

E = alkalinity of the elutriated sludge

D = alkalinity of the unelutriated sludge

R = volume ratio of the wash water to the sludge to be elutriated

W = alkalinity of the wash water

n = number of times sludge is washed

Sludge and wash water can be mixed in pipelines feeding the elutriation basins, in separate mixing chambers, or in the basin itself. The primary mixing requirement is to provide intimate contact of the water and sludge. Usually 20 to 30 seconds of vigorous mixing is adequate.

Elutriation basin overflow rate and solids detention time are critical design parameters if maximum solids capture and sludge solids concentration are required. Experience at New York indicated that overflow rates were less than 400 gpd per square foot(171). Because poor solids capture is such a common problem, rates nearer 200 gpd per square foot seem more reasonable. MacLaren(53) recommended solids loading rates of 8 to 10 pounds of dry solids per square foot per day, but others believe 10 to 15 pounds per day per square foot is satisfactory. The optimum rates for any specific location depend on the sludge characteristics and subsequent dewatering processes.

Because elutriation is normally followed by vacuum filtration of the sludge, maximum solids concentration is a worthwhile goal in the design of elutriation basins. Sparr reported that 12 hours should be the absolute minimum detention time but 24 hours is preferable(170). Data from New York confirmed Sparr's statement(171). The New York data were based on detention of the solids in the sludge blanket, not the liquid detention period. Sludge blanket depths at New York were limited to less than 3 feet; this appears to be a good operational procedure for most sludge handling operations.

Genter believed that the concentration of volatile solids in the sludge to be elutriated was an important design consideration. The New York data by Torpey and Lang illustrated this point(171). Figure 8.II shows significantly lower solids concentrations being attained with increasing percentages of volatile solids. Lower solids loading rates were necessary to compensate for the increased volatiles.

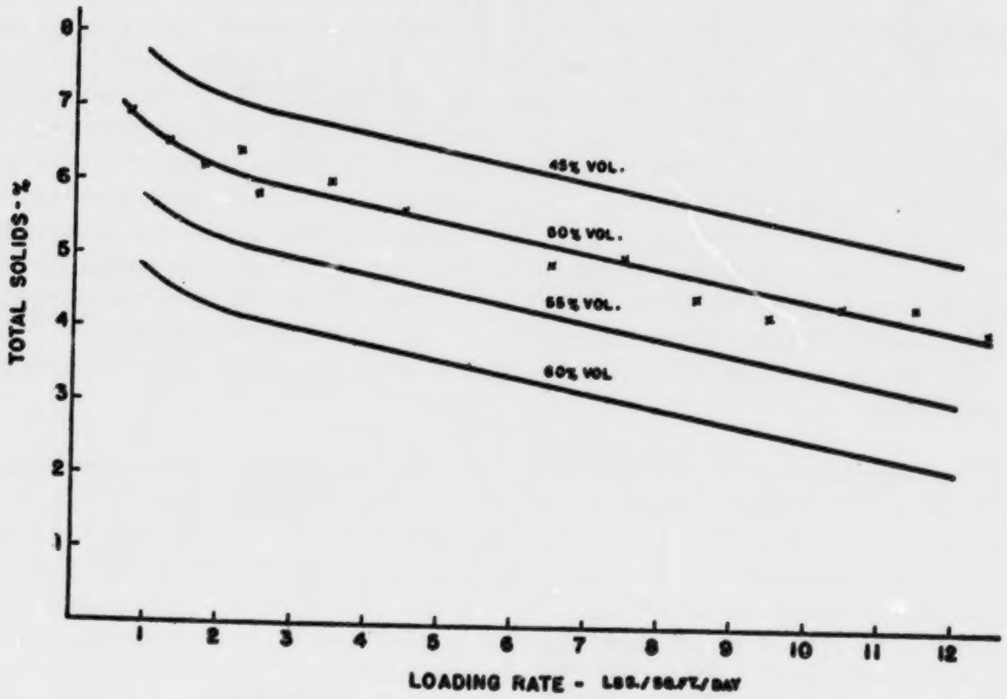
The design of elutriation systems is very important. Many of these systems operate inefficiently and thereby decrease overall plant performance. The effective separation of the sludge particles and the water used to wash the sludge is difficult(66). To accomplish a good separation, tanks must be loaded at low rates,inlet velocities must be slow, tanks should be baffled and effluent weir loading rates must be small. Akron, Ohio, secured significant increases in elutriation efficiency by: (1) lengthening the tanks 45 percent, (2) installing a longer overflow weir, and (3) adding scum collectors. These changes were responsible for a reduction in the concentration of elutriate solids from one percent to one-tenth percent(178). A maximum weir loading of 5,000 gallons per foot per day is often recommended.

Chemical Reduction - The primary justification for the elutriation process is to remove digested sludge constituents that inhibit chemical flocculation before sludge dewatering by vacuum filtration. Elutriation appears to be the simplest method of reducing the flocculent demand exerted by the liquid portion of the sludge. Various authors have stated that elutriation eliminates the need for lime completely and reduces the ferric chloride dosage by 50 to 80 percent. Often, however, when reviewing performance records the requirement for lime was not completely eliminated by elutriation and the ferric chloride dosage was reduced less than 50 percent.

Genter's diagrams in Figure 8.III show the relative flocculent demand by the solid and liquid portion of the sludge for different types of sludges: (a) primary, (b) primary and filter humus, and (c) primary and waste activated(21). According to Genter's data, digestion lowers the solids demand and elutriation lowers the liquid demand.

Figure 8.IV shows the relative dose of ferric chloride for varying degrees of elutriation at Washington, D. C.(175). Obviously, elutriation effectively reduces the requirement for ferric chloride. McNamee conducted some tests to prove that bicarbonates are responsible for the high ferric chloride dosages associated with

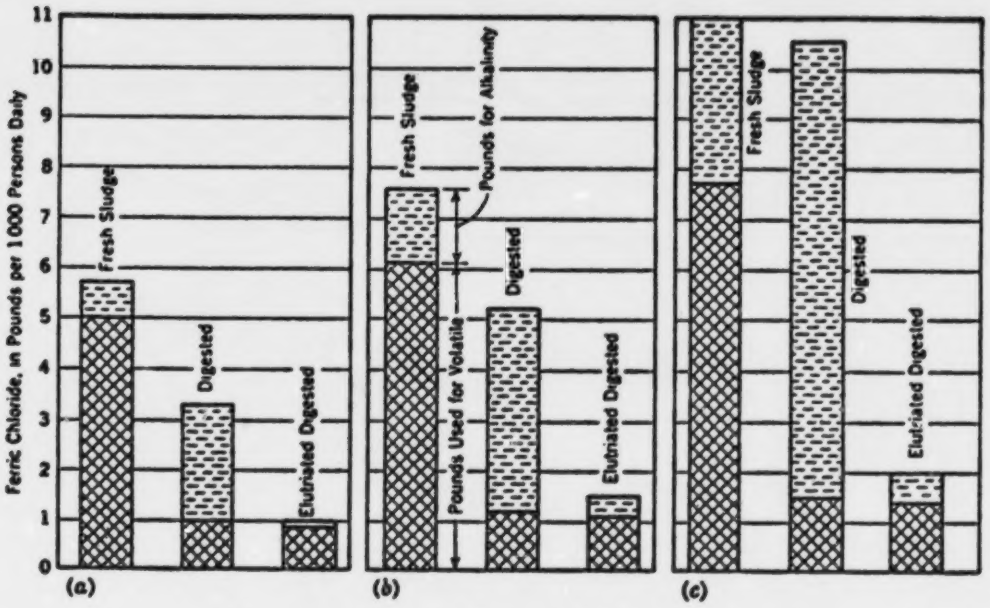
Figure 8.II



**Relation of loading rate to concentration for various per cent volatile sludges.**

(Reprinted by permission from Vol. 24, No. 7, p. 819, July 1952, Sewage and Industrial Wastes)

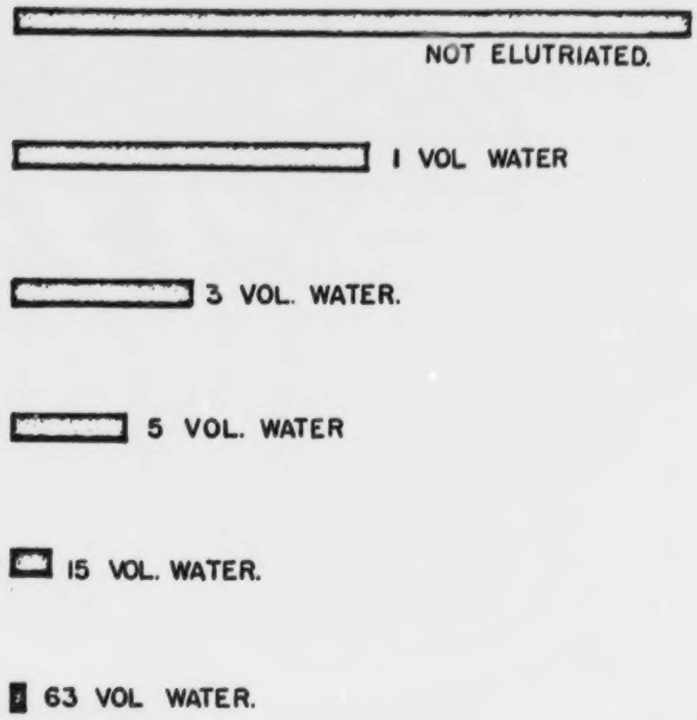
Figure 8.III



**Quantity of ferric chloride required for vacuum filtration of various domestic sludges.**

(Reprinted by permission from Vol. 28, No. 7, p. 836, July 1956, Sewage and Industrial Wastes)

Figure 8.IV



Relative doses of ferric chloride for varying degrees of elutriation.

(Reprinted by permission from Vol. II, No. 9, p. 766, September 1939, Sewage Works Journal) digested sludge(175). After filtration tests on washed sludges to which ammonium salts and bicarbonates were added, he concluded that the amount of ferric chloride needed to condition sludge is related to the bicarbonate concentration and is influenced very little by the ammonium ion. McNamee and others believe lime as a sludge conditioning agent is of little value in dewatering elutriated sludge.

Elutriation is particularly valuable where the digested sludge contains some waste activated sludge. This sludge, if unelutriated, has an extremely high flocculent demand. At the Los Angeles Hyperion sewage plant, the digested primary and waste-activated sludge had to be elutriated before normal operation. The chemical cost without elutriation was $20 per ton and with elutriation, $4 per ton(180). No one questioned the ability of the elutriation process to decrease the requirement for chemicals. There is, however, the question of the importance of washing out "fine" solids to reduce the chemical demand. Many people believe that the chemical demand is reduced primarily because there are less small sludge particles to condition. These uncaptured particles often end-up in the treatment plant effluent(180).

Sludge Thickening - While the elutriation process was developed for chemical reduction in vacuum filtration, it is also an effective sludge thickening technique. Elutriation is successful as a thickening process because it washes out gas bubbles formed during sludge digestion, thereby lessening the buoyant effect on the solids. It also washes out the fines and colloidal material that interfere with sludge concentration(65). In most sludge thickening operations, it is advantageous to dilute sludge particles in order to promote settling and greater solids compaction. Also, the detrimental effects of septicity on concentration are reduced when sludge is diluted with well aerated liquid.

Torpey and Lang concluded that single-stage elutriation was as effective in sludge concentration as a secondary digester having twelve times the volume of an elutriation basin(171). At New York, digested primary sludge was thickened from 2 to 3 percent solids to 3.9 to 7.4 percent solids. The exact figure depended on the sludge volatile content and the basin loading rate.

Intermediate or interstage elutriation has been described by Torpey, Lang, and Kennedy(65b, 171). This process involved the elutriation of sludge being transferred from primary to secondary digesters. The advantages were described as follows:

1. It increased the effective capacity of primary and secondary digesters.
2. It reduced the B.O.D. of digester supernatant liquor, therefore, easing disposal problems.
3. It simplified digester operation.
4. It reduced the chance of digester foaming.
5. It reduced the volume of final sludge thereby saving sludge bed and lagooning space.

At New York, interstage elutriation of digested primary and modified aeration sludge reduced the sludge volume by 30 percent, compared to conventional primary-secondary digestion(176). A 4.9 percent primary digester sludge was washed 4:1; the result was a secondary digester sludge with an average solids concentration of 6.4 percent. There was a loss of digester gas production equal to 10 percent of the normal volume. The New York officials concluded that a 20 percent reduction in sludge volume would justify interstage elutriation.

The San Francisco Richmond-Sunset plant thickened primary digester supernatant solids from 1.5 to 4 - 5 percent in elutriation basins before the solids were pumped to secondary digesters(65b). This technique, called interstage elutriation, increased the final solids concentration by about one-third.

A number of plants that elutriate secondary digester sludge have reported substantial increases in solids concentration. For example, the operating records from the Washington, D. C. sewage treatment plant showed an average increase from 5.7 to 8.9 percent.

Kennedy advised engineers to give special consideration to the design of elutriation basins if sludge thickening is to be a primary goal(65b). Sludge collection equipment and the storage hopper areas of tanks should have extra capacity. Also, the problem of pumping, thickened, elutriated sludge needs special attention, particularly for sludges exceeding a solids concentration of 8 percent.

Chemical Aids - Elutriation solves the high-cost problem of vacuum filtration, but often causes another due to elutriate solids recycle. Recycling uncaptured elutriate solids can overload aeration facilities at activated sludge plants to the point where the overall plant performance is seriously affected. One way to solve this problem is to enlarge the physical facilities so that the solids and hydraulic loadings in the elutriation basins are reduced. Another way to increase the solids capture, thereby improving the elutriate, is to chemically flocculate the fines. The normal procedure would be to add a flocculant to the wash water or sludge-wash water mixture. A less effective method is to return filtrate containing some residual flocculent from vacuum filtration.

The following data from one large activated sludge plant describes possible advantages from the use of an anionic polymeric flocculent (dose of 1.6 pounds per ton) to treat elutriation basin feed(197):

Sludge Type - digested primary and activated

| | Before Flocculent Use | After Flocculent Use |
|---|---|---|
| Elutriated Susp. Solids | 3,835 mg/l | 365 mg/l |
| Solids Capture | 65.1% | 95.3% |
| Underflow Solids Conc. | 3.5% | 4.3% |

Goodman has also reported improved elutriation basin performance after conditioning basin feed with polymers(203). Without chemicals, the zone settling rate was 5 inches per hour. With a chemical dose of 3.5 pounds per ton, the rate was 10 inches per hour and at 7 pounds per ton, 17 inches per hour.

Economics - Many observers agree with Genter that the economy of dewatering digested sludge by vacuum filtration is enhanced by sludge elutriation(172). There is no doubt that it reduces the cost of chemicals. MacLaren, however, pointed out that elutriation basins significantly increased capital costs; he estimated a cost of $2 per ton of dry solids based on a 30 year amortization at 5%(53). Average operating costs were estimated to be 75 cents per ton of dry solids. The total annual cost is, therefore, a little less than $3 per ton.

Yet, data from many sources showed that chemical cost reductions resulting from elutriation substantially exceeded $2 per ton. Considering that lime is usually completely eliminated and ferric chloride is reduced from 50 to 80 percent, it seems easy to justify the economics of elutriation. In addition to the direct chemical cost reduction resulting from the elimination of lime and some ferric chloride, there are the added benefits of less equipment maintenance, improved incinerator performance, descreased quantity of incinerator ash to be disposed, elimination of ammonia odors, and less chemical handling. In terms of dollars these added benefits can be very important. But, any economic evaluation must also consider the added cost of treating recycled elutriate.

Evaluation and Summary - The elutriation process has been proven to be a useful tool for reducing the cost of dewatering digested sludge by vacuum filtration. In fact, in the case of digested sludge containing waste activated sludge, it may be a necessary process if reasonable dewatering costs are desired. Since chemical conditioning is a major cost and nuisance factor in the vacuum filtration of sludge, elutriation can be used to minimize these factors in sludge conditioning.

Elutriation can also thicken digested sludge by diluting and degassing solids. Thickening, of course, reduces the cost of subsequent sludge disposal processes, such as barging and lagooning. Using interstage elutriation between primary and secondary digesters, elutriation results in increased digester capacity and improves the supernatant liquor. Elutriation of dirty digester supernatant liquors can break the cycle of suspended solids recirculation in a treatment plant(172).

Treatment plants reporting operational problems with elutriation usually complain about poor recovery of fine solids. At Los Angeles, 40 percent of the elutriated solids escaped to the ocean(180). This could have caused a serious problem if the ocean had not been available for elutriate disposal. A gradual build-up of recycling elutriate solids can jeopardize the efficiency of activated sludge processes by exerting excessive requirements for oxygen. At New York, the elutriate has contained from 5 to 30 percent of the solids applied(171).

The problem of losing solids in the elutriate has been solved in three ways. First, additional elutriation basins have been constructed to decrease the solids and hydraulic loading rates to a level conducive to good solids capture. Second, flocculents have been used to agglomerate the fine solids causing them to settle more effectively. Third, the elutriation basins have been operated on a batch basis rather than a continuous basis. Batch operation produces a much better elutriate but it sometimes is not feasible due to limited facilities or labor. The importance of the solids demand in relation to the liquid demand in a sludge chemical conditioning process is shown when one of the above techniques is used to increase the capture of fine solids. Chemical conditioning costs increase greatly due to the flocculent demand exerted by the fine solids washed out of the elutriation basin.

Another disadvantage of elutriation results from the washing out of nitrogen compounds in the sludge. This decreases the value of the sludge as a fertilizer and ultimately results in a higher concentration of nitrogen compounds in the treatment plant effluent. Increased fertilization of the receiving water is a major water pollution control problem.

Many consulting engineers do not consider elutriation when designing new waste treatment facilities. They believe the loss of solids in the elutriate is unavoidable and, therefore, the process is unsatisfactory even if high chemical costs for mechanical dewatering are required as a substitute. Better process design and operation or the use of chemicals can solve the major operational disadvantage of elutriation--poor solids capture, but this would eliminate what may be the major function of the process -- washing out fine solids. Genter(172) over-emphasized the importance of the liquid flocculent demand. Capturing these solids in the elutriation tank would, therefore, destroy the objective of the process.

Perhaps the best solution to the above dilemma is to treat the elutriated solids separately or in combination with solids contained in digester supernatant, thickening tank overflow, filtrates, and centrates. For example, these solids could be dried on sand drying beds. Another possibility is to add lime to the combined liquid wastewater and sell the mixture as a liquid fertilizer. This and other new approaches should be evaluated soon.

## 9. LAGOONING - LANDFILLING

General - Lagooning is the most popular sludge disposal technique at industrial wastewater treatment plants. It is also a very popular method for disposal of sewage sludges and water treatment plant sludges. Lagoons may be natural or artificial depressions in the ground. They may be used for either digested or undigested sludge. However, using lagoons to store raw organic sludges such as sewage sludge is rare due to problems of odor and insect breeding. Lagooning may be considered as a stage process in the handling of sludge or as a final sludge disposal process. Some lagoons are used only in emergency situations when other sludge handling processes are temporarily overloaded or out-of-service. Because lagooning is cheap and simple, it will continue to be a popular sludge handling and disposal technique until land becomes so valuable that space limitations force the use of another process.

Landfills are used as final disposal sites for dewatered sludges of all types. If the distance from the treatment plant to the disposal area is not too great, landfilling can be a relatively inexpensive disposal technique.

Classifications - Lagoons may be divided into three classes(70): (1) thickening, storage, and digesting lagoons; (2) drying lagoons; and (3) permanent lagoons.

The first type of lagoon is used for thickening, storage, and digestion of sludge when mechanical thickeners, storage tanks, and conventional digestion units are overloaded or sometimes as substitutes for conventional processes. When used as a substitute, there should be multiple units and equipment for decanting the overhead liquid and returning it to the head of the treatment plant. Digestion in a lagoon can be a lengthy process and one that creates multiple nuisance problems. After digestion is complete, the sludge can be discharged to sand drying beds for dewatering.

Drying lagoons are used as substitutes for sand drying beds. The sludge is periodically removed and the lagoon refilled. Many months are required to dry the sludge sufficiently for removal, so multiple units must be provided. Two lagoons could be operated in series, the first receiving the heavier solids while the second receives the lighter solids decanted from the first. The sludge may not dry to less than 70 percent moisture, but at that point, it can be removed by mechanical excavation(70). After removal, the dried sludge can be used as a fertilizer or soil conditioner.

A permanent lagoon where the sludge is never removed, or at least not removed for many years, is one of the cheapest methods of sludge disposal. Many plants, both large and small, use this technique. It is obvious that large and inexpensive land areas are required to justify this method rather than other sludge disposal methods. A supernatant liquor decanting system is recommended to optimize the usefulness of permanent sludge lagoons.

Parameters and Design - Some of the parameters related to lagooning are: (1) land area, (2) climate, (3) subsoil permeability, (4) lagoon depth, (5) lagoon sludge loading rates, and (6) sludge characteristics.

Lagoons are often constructed in areas where the soils are porous unless contamination of the ground water is a threat. Many states require that the lagoon bottom is at least 18 inches above the maximum water table level in order to prevent contamination(58). If permeable sandy or gravel-type soils are unavailable, under-drains may be constructed to facilitate removal of the drainage water. Some observers, however, believe that under-drains do not benefit the drying process.

The design of lagoons should provide for uniform distribution of the sludge when applied and for an easy method of removing the dry solids. MacLaren recommended a discharge system that limits sludge travel to 200 feet. He also recommended diked embankments with a 1:2 slope on the exterior side and 1:3 on the interior to prevent erosion(53). The width of the embankment at the top should be sufficient to allow vehicle transport during the cleaning operation. Again, provisions for supernatant decanting should be provided to promote drying. Decanted supernatant can be returned to the treatment plant influent.

Jeffrey made some interesting observations about lagooning based on laboratory studies relating sludge drying to drainage, evaporation, and transpiration(205, 216). He observed that drying caused by drainage is independent of lagoon depth, at least during the first 20 days, and does not produce a sludge sufficiently dry for easy removal. Therefore, evaporation or transpiration is necessary for satisfactory lagooning. Areas where climatic conditions encourage evaporation are particularly conducive to lagoon operations.

Jeffrey also conducted a laboratory study which related lagoon depth, soil permeability, and dewatering rates(216). He loaded a "lab lagoon" to 18.7 feet with 8 percent sludge; it dewatered to 3.7 feet. The study concluded initial dewatering rates were affected by supporting media permeability. However, after a short time, the rate decreased and the effect of the support media was insignificant.

Solids loading criteria for lagoons have been recommended by VanKleeck(8):

| | | |
|---|---|---|
| (1) | Raw sludge<br>(Using lagoon as a digester) | 6 lbs/yr./cu. ft.<br>of lagoon capacity |
| (2) | Digested sludge<br>(Using lagoon for dewatering) | 2.2 to 2.4 lbs./yr./cu. ft.<br>of lagoon capacity |

Others have prescribed a loading rate of 500 tons per acre(368). Jeffrey quoted loading rates for lagoons in Canada as being 1.84 pounds of dry solids per square foot of lagoon per 30 days of bed use. In this case, the sludge was removed after 18 months(216). He also reviewed the Iowa City experience where the loading rate was 1.7 pounds of dry solids per square foot per 30 days of bed use.

Lagoon performance is affected by rainfall and temperature so these factors should be considered in the design and operation.

Operation - The standard operating procedure for lagoons is to discharge digested sludge to the lagoon at regular intervals as determined by the solids accumulations in digesters(205). Jeffrey proposed a 3-year cycle for lagooning digested sludge(216). The lagoon is loaded through one year; it dries for 18 months and is cleaned; and finally the supporting media is "rested" for six months. In northern climates this operation would start in November. Three lagoons are necessary for operational flexibility.

When the lagoon is used for dewatering and not permanent storage, MacLaren recommended filling to a depth of from 2.5 to 4 feet, (the greater depths in warmer weather)(53). He believed the best filling practice was to add one foot of sludge, switch to another lagoon to permit some drying in the first unit, and then add the remaining amount to the first lagoon. A 4-foot depth provides 2 to 3 years' capacity, assuming one wet year in that period. This schedule is equivalent to a loading of 40 pounds dry solids per square foot per year. Bubbis suggested a similar schedule: filling lagoons with 10 inches of well digested sludge, allowing it to settle for 14 days, decanting the supernatant liquid, and repeating the process until the lagoon is full of sludge(204).

Eventually the "dried" sludge must be removed from the lagoons or new lagoons constructed. Sometimes if natural low-lying land is filled by sludge lagooning, removal is not necessary because the objective may be land reclamation. MacLaren reported that minimum cleaning costs for Winnipeg lagoons are achieved by using rippers during winter months and removing the dislodged sludge by earth-moving equipment(53). Dredging the top layer of sludge by dragline after a 3-month drying period speeds up the dewatering of lower sludge layers(70). Berger reported that paper-mill sludge lagoons require cleaning or expansion every 3 to 5 years(51).

Dried sludge removed from lagoons is landfilled or used as a soil conditioner on parks or other areas.

Performance - Sewage sludge stored in lagoons may be dewatered from about 95 percent moisture to 55 or 60 percent moisture in a 2 to 3 year period(53). In England sludge dewatering to less than 70 percent is rare(70). Many large cities have used sludge lagoons satisfactorily for many years. These cities include Chicago, Philadelphia, Dallas, Fort Worth, Akron, and Toledo. The literature contains very little performance data from either large or small treatment plants, describing the efficiency of lagoons.

This lack of information may reflect the fact that lagoon operations can be simple, economical, and satisfactory to all concerned. However, lagoons are not a panacea. The following sections discuss economics and the pros-and-cons of sludge lagoon operations.

Economics - Lagooning of sludge is popular because it is often cheaper than any other dewatering or disposal technique. Most industrial sludges are lagooned for this reason. For example, industrial sludge is frequently inorganic and, therefore, creates a minimum of odor; thus, a sludge digestion step preceding lagooning is not required. Also, many industrial sludges, such as oil and metal finishing sludges, are lagoon-dried because they are difficult to dewater by vacuum filtration.

MacLaren stated that lagoons can be constructed at an approximate cost of \$12,000 per acre or \$1.10 per ton per year, based on 30-year amortization at 5% interest(53). This cost included land and all piping. He also stated that cleaning costs range from \$1,000 to \$2,000 per acre per year depending on ultimate sludge-disposal points, or \$1.20 to \$2.40 per ton of dry solids applied to the lagoon. Berger reported that lagoon cleaning costs for paper mills were \$2.00 to \$3.00 per ton of dry solids applied(51). Because these lagoons are undeveloped land depressions, this figure is an estimate of the total sludge disposal cost. The cost of excavation and diking has been about \$0.48 per cubic yard for southern paper mills. Lagoon drying at Winnipeg cost \$0.80 to \$1.00 per ton, excluding lagoon maintenance(204).

In Green Bay, Wisconsin, 20 acres of lagoons were constructed at a cost of \$50,638 (or \$2,530 per acre) in 1960. It was estimated that 25 years will be required to fill the lagoons, so operating costs (cleaning) are insignificant(214).

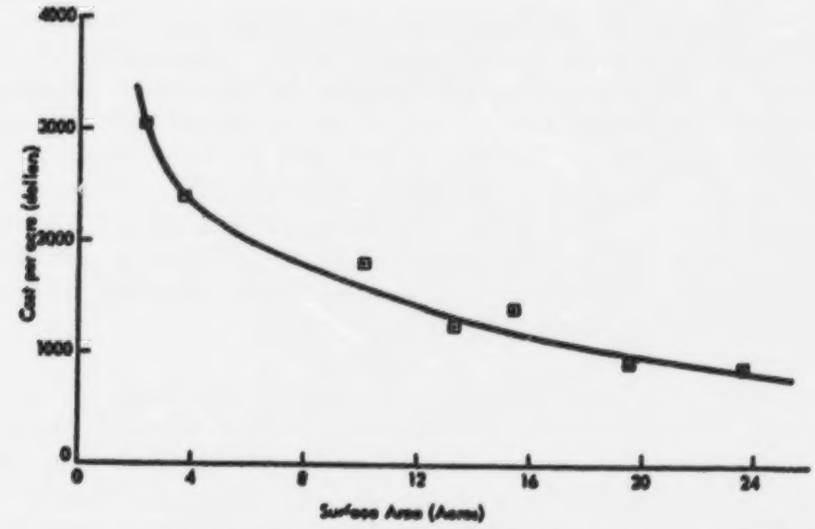
Howells and Dubois studied the cost of sewage stabilization ponds in the midwest(206). Representative costs of sludge lagoons are shown in Figure 9.I. Multiplying the cost from the graph by a factor of 1.2 accounts for the increase in the ENR Cost Index. Caron reported that sludge disposal in shallow lagoons costs between \$1.00 and \$3.00 per ton depending on hauling costs and final sludge moisture(44).

An average lagoon capital and operating cost ranges from \$1.00 to \$3.50 per dry ton of solids handled. These costs include an assumption that lagoons are near the wastewater treatment plant. If the sludge has to be piped long distances, the costs would naturally be greater.

The operating cost for sanitary landfills is generally considered to be \$0.50 to \$2.00 per ton(3, 69, 352). Average capital costs are about \$1.00 per ton. These figures appear very low but hauling costs of the dewatered sludge determine whether landfilling can be economical. If they exceed \$5.00 per ton, incineration of the sludge may be a cheaper means of disposal.

Summary - Lagoon disposal of well digested sewage sludge and many industrial sludges is a very common practice basically because it is economical. In addition, lagoons have the advantages of simplicity of operation, flexibility, and suitability for plants

Figure 9.I



-Stabilization pond costs in Missouri based on a statewide average cost of excavation and adjusted excavation quantities.

(Reprinted by permission JWPCF, Vol. 31, No. 7, p. 815, July 1959) of any size. Sludge disposal to lagoons can be a regular operational procedure or used temporarily during peak-load periods or when other disposal processes are out of service.

Lagoons are usually located at the treatment plant site when land is available. If inexpensive land is not available close by, it is often economical to pump sludge to remote areas within 5 to 10 miles of the treatment plant.

Lagoons, however, are not applicable to all sludge disposal situations. For example, they can be a source of odor and insect nuisance if used for the disposal of raw sludge or incompletely digested sludge. Their satisfactory use depends, in the latter case, on a well-operated treatment plant. Odor control chemicals could be applied when nuisance problems develop, but their use has rarely been satisfactory.

Two other disadvantages of lagoons are the large land area required and the possibility of ground water pollution. Lagooning of all sludge at medium to large-size urban cities is uncommon because land is too expensive or unavailable. Ground water pollution by microorganisms or toxic industrial wastes is a threat that must be considered in the design of sludge disposal facilities. These same two disadvantages, large land area requirement and potential for ground water pollution, are also applicable to sanitary landfills. In addition, landfills have the disadvantages of needing cover dirt, and their operation is affected by the weather.

Lagooning of sludge will continue to be popular so long as inexpensive land is available relatively close to the treatment plant site. However, such land becomes less available as population and manufacturing grows. The trend to mechanical dewatering already is obvious; space that might have been used for lagoons is now being used for landfilling mechanically dewatered sludge cake. More expensive but more compact sludge disposal processes will be substituted for lagoons in the future. As landfill areas disappear, especially in large urban areas, incineration processes will be installed.

## 10. LAND DISPOSAL OF LIQUID SLUDGE

General - A survey of consulting engineers and State Pollution Control Agencies revealed that the disposal of liquid digested sewage sludge to open land surfaces is very common among smaller waste treatment plants(25). Large cities such as New York, San Diego, and Miami Beach have also used this technique of sewage sludge disposal in conjunction with land reclamation projects. In England, the disposal of liquid sludge to farmland is very popular. The process is often economically attractive because it eliminates a costly solid-liquid separation step. But, land disposal of liquid sludge can be very expensive if truck hauling distances are very long.

Liquid digested sludge and supernatant liquor are being applied to land for final disposal, to fertilize grass or agriculture crops, and to condition soils on sandy park land. These operations have been very satisfactory with few exceptions. The success of this sludge disposal method usually depends on the availability of suitable land close to the waste treatment plant. Pumping the sludge to disposal areas within 10 miles of the treatment plant is usually justifiable but less control is possible than with disposal near the plant site. Liquid sludge disposal is regulated by health authorities because nuisance conditions from odors and insects are possible, and potential public health hazards from microorganisms need to be considered. The disposal of liquid sludge in association with composting is discussed in the Compost chapter of this report.

Parameters and Operations - Digestion, aerobic or anaerobic, is almost always required before disposing of liquid sewage sludge. Nuisance-free disposal requires the sludge to be well digested; therefore, the plant operator has a responsibility for good treatment operation. Climate influences the disposal of liquid sludge; for example: sludge cannot be hauled onto farmland during wet weather. Digesters and lagoons are usually designed with excess capacity so they can be used for storage until the weather permits hauling.

Sludge is distributed on the land and processed in a variety of ways. Treatment at small plants may include only digging of shallow trenches, filling them with liquid raw or digested sludge, and covering the sludge with soil to prevent nuisance conditions. Sludge may be pumped or gravity fed through pipelines to agricultural fields or land to be reclaimed. At some orchards, the liquid sludge is injected into the subsoil under pressure. A very common technique is disposal of liquid-digested sludge directly to land by spraying from tank wagons having a capacity of 1,000 gallons. Large unloading lines hasten disposal and thereby reduce labor costs.

Agricultural land is best used by clearing the previous crops, plowing deeply, and forming furrows to contain the liquid sludge. An ideal sludge-application system uses a two-step procedure; a shallow layer is spread, dried, harrowed, followed by a deeper application of sludge with drying and harrowing. Multiple applications at low dosages form a thin sludge layer that is easily worked into the soil. A sludge loading on cropland of 100 dry tons per acre is successful under average conditions. In areas of low rainfall, 300 tons per acre is practical(368).

Land reclamation by spreading liquid digested sludge is practiced in some coastal areas. In New York City, barges and tank trucks are used to transfer liquid digested sludge from sewage treatment plants to a disposal site where the sludge is pumped into a pipe distribution system for application to the land. Liquid sludge is dried 2 to 3 days and then disced into the soil. This process is repeated about 16 times in an area until 4 inches of topsoil are formed from a mixture of sludge and sand(369, 372). At San Diego, land reclamation incorporates furrow plowing in the sandy soil, filling with liquid sludge and immediate covering of the furrow. After drying for 1 to 2 weeks, cross furrows are plowed and the process repeated(389). One thousand tons of sludge have been applied per acre.

The canning and paper industry investigated the disposal of wet solids by spray irrigation. Solids are disintegrated and sprayed with liquid wastes through irrigation piping. For this process, a good, inexpensive, solids grinder is required for successful disposal of wet solids(216, 402).

Performance - Studies at San Diego, California, have generated significant performance data concerning liquid sludge-disposal. From studies of a digested-sewage sludge described in Table 10.1(369), Nusbaum and Cook made the following conclusions(389):

1. Liquid sludge can be used to reclaim waste land for agricultural purposes at a lower cost than heat-dried sewage sludge.

2. Sludge can be applied at a rate of 100 tons per acre without impairing the growth of crops.

3. Applying sludge at a rate of 25 tons per acre achieves a crop growth rate equal to that of commercial fertilizers applied at conventional rates.

4. Superior crops can be attained over a 2-year period at a sludge dosing rate of 50 tons per acre without applying sludge the second year.

5. Liquid land disposal can be achieved without serious handling or nuisance problems.

Table 10.1
ANALYSIS OF DIGESTED SEWAGE SLUDGE - SAN DIEGO
(Results in Percent, Dry Basis)

| | Prior Average | Average During Spreading |
|---|---|---|
| Total dry solids | 3.44 | - |
| Grease | 11.15 | - |
| Fatty acids | 24.23 | - |
| Chlorides | 0.75 | 0.87 |
| Total nitrogen | 2.73 | 2.78 |
| Phosphorus as $P_2O_4$ | 4.78 | 4.70 |
| Sodium | 1.07 | 0.56 |
| Potash as $K_2O$ | 0.83 | - |

The San Diego studies demonstrated the usefulness of liquid sludge as a fertilizer for agriculture crops, grasses, and shrubs, and as a soil conditioner for relatively sterile dredged sand(10, 368, 369). Many acres of sandy soil in the Mission Bay Park have been reclaimed by the use of sludge to build topsoil. A 7-mile pipeline from the new San Diego treatment plant conveniently delivers the digested primary sludge to the park area. It has been estimated that the use of liquid sludge eliminated the need to import one million cubic yards of topsoil to Mission Bay Park(10).

In New York City, land, proposed for future parks, has been reclaimed by spreading liquid sludge in place of natural topsoil.

In 1956 five million cubic feet of liquid digested sludge was sprayed on landfill areas prior to a dressing of topsoil(372). The sludge was also used on sandy tidal areas devoted to a bird santuary. These sludge land-disposal operations were satisfactory on the basis of cost and performance. They served as an inexpensive method of sludge disposal and at the same time provided a cheap topsoil material.

Scott reported on the use of a 5 to 6 percent total solids whey waste as a liquid fertilizer(365). Crop yields of land receiving the waste increased if the loading did not exceed 50 tons per acre per year. No odors developed at this loading, but higher rates produced both odor and insect nuisance problems. Canham described the application of wet cannery solids to land(385). After comminution to particle sizes of about one-eighth inch, the solids were sprayed with liquid wastes through irrigation piping. The solids did not form a mat in the fields and did not produce odors if the application rate was not excessive. It was suggested that a variety of crops could benefit from the land disposal of comminuted cannery solids because they contribute beneficial humus to the soil.

Caron and Blosser studied the efficacy of land disposal for dilute papermill sludges(402). The system proved to be feasible because cellulose is decomposed by aerobic and anaerobic bacteria in the soil. The rate of cellulose decomposition was influenced by the nitrogen content, as indicated by the following lab data:

| | | | |
|---|---|---|---|
| 90% cellulose decomposition achieved in: | 45 days | 50 days | 80 days |
| with carbon:nitrogen ratios of - | 5:1 | 10:1 | 550:1 |

Loading rates of 20 to 25 tons of sludge per acre per year were feasible.

The use of liquid organic sludges on land improves the soil structure, its moisture retention ability, and it contributes valuable nutrients to stimulate vegetative growth.

Economics - Liquid sludge disposal at San Diego offers a stark example of favorable economics in comparison with mechanical dewatering and heat drying. Between 1951 and 1956, the average solids handling costs were about $40 per ton. This figure included sludge digestion, elutriation, vacuum filtration, and heat drying(369, 389). Because the dried sludge was sold as fertilizer at about $5 per ton, the net cost for solids handling was approximately $35 per ton of dry solids. Average liquid sludge disposal costs during 1959 and 1960 were $9.91 per ton (sludge solids = 6%). Of this total, $2 per ton was spent on preparing and finishing the site disposal area. The truck haul was 21 miles round-trip at a cost of $0.0019 per gallon(389). Hauling liquid sludge eliminated the need for sludge elutriation which was a source of water pollution and increased use of chlorine because of the poor, solids-capture efficiency in the elutriation basin. San Diego included a pipeline for sludge transport when they constructed their new treatment plant, so the solids handling costs were further reduced to about $4.00 per ton, $1.50 per ton for pipeline operation and maintenance and $2.50 per ton for site preparation and finishing.

In New York liquid sludge disposal to land areas cost about the same as barging costs or $7.50 per ton of dry solids. They estimated that many thousands of dollars have been saved by substituting digested sludge for natural topsoil. The in-place cost for sludge was reported to be $1,600 per acre while the cost for natural topsoil is $4,500 per acre(372).

Some cities sell their liquid digested sludge to private groups; others less fortunate must give it away or even pay someone to haul it off the treatment plant property. A few examples of each situation have been reported:

1. Orlando, Florida, sells liquid digested sludge to fruit growers for $1.00 per 1,000 gallons(24).

2. Two northwestern cities sell their liquid sludge for $2.00 to $10.00 per 1,000 gallons f.o.b. the treatment plant(359).

3. In California, liquid sewage sludge is often blended with other materials and sold as fertilizer. The sludge is usually given free-of-charge to commercial fertilizer companies or sold at a cost less than $2.00 per dry ton.

4. Olympia, Washington, is paid $4.00 per ton and Chehalis, Washington, $10.00 per ton for liquid sludge. At Chehalis, the sludge is hauled to hayfields(359, 365).

5. Some cities and industries in the midwest pay $7.00 to $10.00 per 1,000 gallons to have their waste sludge hauled to disposal sites(28).

Canham believed that the capital investment and operating costs for disposal of pea wastes favors land disposal by comminution and spray irrigation instead of solids separation and hauling to landfills(385). He estimated the annual cost for liquid waste disposal to be 64 percent of the solids separation and landfill technique. MacLaren estimated the cost of liquid sludge disposal to land in Canada to be $5.00 to $10.00 per 1,000 gallons of sludge hauled. Assuming a sludge concentration of 5 percent, this cost is relatively expensive ($20 to $40 per ton of dry solids)(53).

Not including digestion, liquid sludge disposal generally costs $4 to $30 per ton of dry solids. The average cost is about $10 per ton. Including the capital and operating cost for anaerobic digestion increases the range to $8 to $50 per ton and the average to $15 per ton.

Summary - Disposal of liquid digested sludge on land areas is quite popular in the United States and foreign countries. Basically, the reasons for this popularity are simplicity and economy. A close look at the advantages reveals:

1. The process represents final disposal because the sludge is normally hauled off the treatment plant grounds by someone assuming responsibility for the material.

2. The sludge is useful as a soil conditioner and fertilizer; therefore, it often can be sold for $1 to $10 per 1,000 gallons.

3. Small capital investment is required, particularly if a contract for hauling is negotiated. Many consulting engineers routinely design digester piping with enough flexibility for loading tank trucks. The required additional piping costs very little.

4. Complex mechanical operation and the use of chemicals is avoided.

5. Related to item (4), solid-liquid separation processes can be eliminated, thereby improving treatment plant economics and efficiency. Overall treatment plant efficiency is improved because there is no need for digested sludge elutriation and dewatering, steps that usually produce a recycle of fine solids in the treatment processes.

The major negative aspect of land disposal for liquid sludge is that it is not applicable to all waste treatment plants, mainly because acceptable disposal sites are not always conveniently available. Hauling costs to acceptable areas can be very expensive because large quantities of water are included with the sludge solids. Land disposal areas must be within a short hauling distance of the treatment plant if a pipeline is not available for sludge transportation. If the disposal area is not owned by the sludge discharger, the success of this technique depends on continued acceptance by the land owner. One application of odoriferous sludge could result in a law suit and the denial of the disposal area to the discharger.

Digestion of sewage sludge, and perhaps some types of industrial sludge, is a prerequisite to acceptable land disposal. This means of stabilizing sludge is costly and must be considered in an evaluation of alternative disposal methods. Anaerobic digesters serve as storage tanks which is necessary provision for liquid sludge disposal systems because weather delays tank-truck hauling to farmland. The use of liquid sludge as a fertilizer or soil conditioner also involves public health considerations. California has adopted regulations preventing the use of sludge for fertilizing vegetables, berries, and low growing fruit unless the sludge has been digested for 30 days, is practically odorless, drains readily, and has a volatile solids concentration less than 50 percent(369). The Ontario Water Resources Commission restricts the use of liquid sludge fertilizer to crops that are cooked before consumption(53).

Liquid sludge disposal will continue to be popular at small plants because it offers many advantages. The hauling costs may be high on a per ton basis, but the total volume of sludge and the total operating budget for its disposal are not very great. Also, the number of sludge handling processes and their related mechanical equipment is minimized. MacLaren considered land disposal of liquid sludge to be applicable to all plants serving less than 50,000 persons(53). San Diego and New York have proven its application to large cities where adequate land disposal areas are available. It is a technique that should be considered even if the sludge has to be transported 10 to 15 miles by pipeline. Economically, land disposal can be promising especially if the sludge producer does not have to pay to have the material hauled away. In this case, solids handling ends at the digester. Additional information is in the chapters on Pipeline Transportation and Sludge As a Fertilizer or Soil Conditioner.

## 11. PIPELINE TRANSPORTATION

General - Many large cities pump sludge relatively long distances through pipelines. The list includes Chicago, Philadelphia, Cleveland, Camden, San Diego, and San Francisco. Pumping is done to optimize sludge handling and disposal costs. When a city has multiple wastewater treatment plants, costs are often decreased by centralizing certain sludge handling steps such as digestion and dewatering.

Data - Wirts surveyed various sludge, force-main pumping operations partially summarized in the following table(432):

Table 11.1

| Location | Length (miles) | Diameter (inches) | Total Head (feet) | Sludge Type | Solids Conc. (%) |
|---|---|---|---|---|---|
| Mogden, England | 7 | 12 | 142 | Digested | 4.0 to 5.0 |
| Birmingham, England | 4 | 9 and 12 | - | Digested | 8.5 to 10.0 |
| The Hague, Netherlands | 7 | 8 | - | Digested | 4.0 to 5.0 |
| Los Angeles, Calif. | 7.5 | 24 | - | Digested | 3.73 |
| Chicago, Illinois | 17 | 14 | 210 | Raw | 1.0 to 2.0 |
|  | 5 | 12 | 170 | Raw | 2.0 to 4.0 |
| Cleveland, Ohio | 13 | 12 | 391 | Raw | 3.0 to 4.0 |
| Philadelphia, Pa. | 5 | 8 | 225 | Raw | 3.0 to 4.0 |
| Columbus, Ohio | 5 | - | - | - | 4.0 to 5.0 |

At Mogden, England, the friction loss of the digested sludge is 1.4 times that of water under the same conditions. Birmingham has a friction loss of 2.6 times that of water for "thick" sludge. In general, digested sludge containing 7.5 percent solids has a friction loss about 2.5 times that of water(449). At Chicago, the pressure in the 17-mile line, carrying a 2 percent mixture of raw primary and activated sludge, varied from 100 psi at the beginning to 4 psi at the end.

Operating and maintenance costs for pumping sludge are $1.00 to $2.00 per ton for Cleveland and other cities. Capital costs, of course, vary with the length of the pipeline, costs of easements, and other factors. Total annual costs of existing sludge pipeline systems are probably $3.00 to $7.00 per ton of dry solids.

Wirts proposed the interesting idea of pumping sewage sludge 80 miles to abandoned, coal strip-mines(432). In addition to being a means of sludge disposal, he suggested that alkaline digested sludge could partially solve the acid mine drainage problem. A pipeline service charge of 10 to 15 cents per ton mile is suggested for cities along the pipeline route. Wirts believed this sludge disposal technique would be much more economical than the $40 or $50 per ton spent on other disposal methods.

Summary - Transporting wastewater sludges by pipeline deserves more attention by researchers and design engineers. It can be simple, inexpensive, and relatively trouble-free. Being an enclosed system the operation is practically odor free. Most important, pipeline transportation can reduce sludge handling and disposal costs.

As is practiced in a number of cities, combined dewatering and ultimate disposal of sludges from multiple sources can be more economical than separate systems. Perhaps in urban-industrial areas, all wastewater sludges from all sources could be pumped to a central handling and disposal treatment plant. Combining a variety of industrial and sewage sludges could have the secondary advantages of neutralizing pH, odor control, sludge lubrication, and disinfection.

Pipeline transportation allows flexibility in ultimate disposal techniques. It permits the relocation of large quantities of sludge away from land-short urban areas, where air pollution regulations are in effect, to less populated areas or the ocean where disposal methods are feasible. Land disposal methods could include lagooning, liquid land disposal as a fertilizer, underground disposal, and disposal in quarries. The cost of transportation might be easily absorbed by savings from relatively cheap methods of disposal not possible in urban areas.

Digestion before pipeline transportation is sometimes specified for non-activated sewage sludges due to potential grease and abrasion problems. Any sludge pipeline system, however, should have the capability of being cleaned at regular intervals without interrupting pumping operations. A design that permits the addition of chlorine to aid pipeline cleaning is also recommended.

The use of pipelines for sludge transportation successfully reduces total sludge handling and disposal costs in many cities. It should be routinely considered in economic evaluations of all sludge disposal systems. One area of needed research is the development of a chemical to fluidize sludge to ease pumping over long distances. Another is a method of preventing sludge septicity during transportation. Also, advanced waste treatment of sludge should be explored to facilitate ultimate disposal at the end of the pipeline. The solids might be used as a fertilizer and the liquid for irrigation. Volumes involved would be much less than the original wastewater, so the costs could be reasonable.

## 12. OCEAN DISPOSAL - DILUTION

General - Sludge disposal by dilution in fresh water is generally unacceptable except for those sludges produced from water treatment plants. However, in large seacoast communities, the disposal of sewage sludge is commonly disposed to the ocean via pipeline or barge. One example of the popularity of ocean disposal is that one-third of the sludge produced in England and Wales is discharged to the ocean(70). Some of the largest cities in the United States, including Boston, New York, and Los Angeles, dispose of their sludge in this fashion. The canning industry in the San Francisco Bay area barges thousands of tons of wet solids each year to the ocean. This technique has the tremendous advantages of being more economical than most other disposal methods. It represents ultimate solids disposal to the treatment plant operator because the sludge is permanently removed from his property.

Obviously, the pumping or barging of sludge to the ocean can be economically justified only for communities or industries on or relatively near the seacoast, but "relatively near" could be a round-trip barging distance of 400 miles. Recent studies by a few, large, eastern cities indicated barging that distance was still cheaper than alternative sludge disposal methods. Disposal of sludge to the ocean has some potential dangers, however, so a thorough scientific study is necessary before adoption of this technique.

Design Requirements - Ocean disposal of sludge normally requires that the following conditions be met:

1. Safe bacteria levels at ocean beaches.
2. No floating solids or scum at the shore line.
3. No objectionable odors.
4. No accumulation of bottom deposits.
5. No concentrations of toxic material detrimental to plant or animal life.

Because raw sewage solids can create a variety of nuisance conditions, it is the usual custom to digest sewage sludge prior to ocean discharge. Digestion changes the nature of the sludge so that it is conducive to rapid mixing and dispersion in the saline water(439). In addition to reducing the volume of solids, it homogenizes the sludge to produce a uniform, end product more predictable upon dilution. A considerable reduction of the pathogenic bacteria population in the sludge and the biochemical oxygen demand is also achieved. Bacteria reductions of 99.8 percent after 30 days digestion at 95 to 100°F have been reported and B.O.D. reductions of 90 percent are possible(439). Digestion also decreases the chance of odor development and damage to aquatic life. Because digestion is so important, over-design of the system is a good idea.

Sludge floatables, if not removed, have a tendency to travel long distances on the surface of the ocean. In that environment they undergo very little physical or chemical change and, therefore, may cause odors, be unsightly, and carry pathogenic bacteria to recreational areas. Floating material can be reduced by burying or incinerating screenings and skimmings rather than letting them pass into the digester. Digestion reduces and homogenizes some of these materials but the process is incomplete. Some West Coast cities practicing ocean disposal screen the digested sludge prior to pumping through the outfall line.

The success of ocean disposal of sludge via pipeline depends in part on the design of the sludge outfall line. Outfall lines have been very thoroughly and scientifically studied in California. They consider the following factors of major importance to the outfall location(446).

A. Beneficial Use of Receiving Water
    1. Shellfish
    2. Bathing
    3. General

B. Public Health
    1. Shellfish
    2. Bathing
    3. General

C. Marine Resources
    1. Fishery
    2. Shell fishery
    3. Other (kelp-game, etc.)

D. Oceanographic
    1. Current structure
    2. Eddy diffusion
    3. Density structure
    4. Wind structure
    5. Submarine
        a. Topography
        b. Geology

E. Nuisance

F. Aesthetic

G. Economic

Sludge must be discharged at a depth that prevents solids from rising to the surface and the discharge must be far enough from shore so that dispersion by currents does not carry the sludge to the shore. Careful planning and investigation of the sludge and dilution water to include specific gravity, temperature, winds, and ocean currents is necessary.

At the end of the submerged outfall line, effective mixing of sludge and seawater is required to promote rapid dilution. The California studies have stressed the need for a sludge diffuser that distributes the flow uniformly at all rates of flow and with maximum dilution near the outfall(446). Mixing the digested sludge with treatment plant effluent or seawater prior to discharge facilitates sludge handling and dispersion(434). Some plants discharge the sludge through effluent lines, others discharge through separate sludge outfall lines. Separate sludge lines, being relatively small diameter pipes, can be installed more economically and, therefore, carried to greater distances and depths than the larger effluent lines.

Operation and Performance - Under some conditions, it may be desirable to discharge the digested sludge to the ocean intermittently. This is done to take advantage of strong currents, ebbing tides, and non-bathing periods when public health problems are not so critical. Digestion offers the advantage of storage flexibility so intermittent discharge is possible(439).

Henry reported that the Vancouver Lions Gate sewage treatment plant stores digested primary sludge until the winter months when favorable ebb tides carry the material rapidly to sea. The sludge is discharged through the effluent outfall line when the tidal flow in the narrows is about 500,000 cfs(441). At the Nut Island sewage plant in Boston, digested sludge disposal is also timed to mix with strong currents. Disposal is through a 4.5 mile, 12 inch line into deep water where the sludge is distributed along the bottom and does not rise to the surface(438). The sludge at Boston is diluted prior to discharge, 40,000 gpd sludge with 1 mgd plant effluent. Once each year the sludge outfall line is cleaned with mechanical cleaning equipment(435).

At the Los Angeles Hyperion plant, digested sewage sludge is diluted with plant effluent to a concentration less than one percent solids before being pumped through a 7 mile, 22 inch submerged pipeline. The outfall line terminates at a depth of 320 feet but the submarine canyon in which the sludge settles is at a depth of 590 feet(435). Dilution to make the sludge-solids characteristics in the pipeline similar to water is thought to be important. The flow is kept continuous and the volume relatively constant(66).

As part of a water quality monitoring program, scientists in California are thoroughly studying the effects of sludge disposal on the marine environment(435). They observed no accumulation of solids around the outfall even though deposition is known to occur. In fact, they estimated that 60 percent of the solids are deposited within 500 feet of the outfall. But, the sludge deposits were periodically removed by ocean currents. Marine investigators reported an increased population of plankton and aquatic animals but no toxic effects on fish have been observed. The long term effects are unknown. Ocean disposal of sludge undoubtedly affects the marine environment. However, with a properly designed system the effect is probably small because the amount of dilution water is so large.

Economics - Of the two methods of ocean disposal (pipeline or barge) pipeline disposal is much cheaper. Operating costs for the sludge outfall line at the Los Angeles Hyperion plant were expected to be $1.15 per ton of dry solids. Before ocean disposal, the cost of producing dried sludge-fertilizer by digestion, elutriation, vacuum filtration, and heat drying was $38.00 per ton. The dried sludge sold for $4.50 per ton, so the net cost was $33.50 per ton(66). Construction of the pipeline cost 2.72 million dollars or $73.50 per foot. In 1951, engineers estimated a 30-inch outfall line on the Atlantic Coast would cost $77.00 per foot(438). Using the ENR Construction Cost Index, the 1966 cost would be $140.00 per foot. Los Angeles is also saving money on chlorine. Before the sludge outfall was constructed, 68 tons per day of solids were lost to the plant effluent line, primarily from the elutriation basins. This material resulted in an extra chlorine demand amounting to $150.00 per day(180).

New York City has been barging digested sludge to the ocean for many years. Their total cost of sludge handling (digestion and barging) used to be about $9.31 per ton of dry solids. Operating and maintenance costs accounted for greater than 75 percent of this total(372). In recent years, New York has reduced the total sludge handling cost to about $7.50 per ton by the use of larger, more mechanized barges plus more rapid unloading of the sludge into the ocean. The round trip distance depends on the treatment plant location, but the average is 25 miles.

Middlesex County Sewerage Authority pays $11.30 per dry ton for disposal of stored chemically precipitated sludge. Their round trip barging distance is 50 miles(448). Barging costs at Elizabeth, New Jersey, are reported to be $4.34 per dry ton(440). Digested sludge is barged from Yonkers, New York, at a cost of $16.05 per dry ton. This figure includes $2.98 per ton capital cost, $5.99 per ton for operation and maintenance, and $7.08 per ton for barge towing. The total cost ($16.05 per ton) compares very favorably with another Westchester County sewage treatment plant---- New Rochelle, New York. There, sludge handling and disposal by vacuum filtration and incineration costs $62.02 per ton.

Four large eastern cities recently evaluated the economics of various methods of sludge disposal. Generally, the economics of barging sludge to the ocean appeared favorable in relation to most of the processes studied.

At Baltimore, Maryland, the sludge handling costs were estimated for the year 1980. Barging costs were based on a digested primary and secondary sewage-sludge mixture having a solids concentration of 7.5 percent. The estimated unit costs were:

| | |
|---|---|
| Barging | $22.81/Ton |
| Heat drying and granulating | $36.40/Ton |
| Incineration | $38.07/Ton |
| Dewatering, mixing with soil | $28.00/Ton |
| Sludge-refuse combustion | $30.00/Ton |

These costs are based on dry solids and include thickening, digestion, elutriation, and vacuum filtration. Equipment related to these processes has already been installed at Baltimore. Capital costs for new facilities were computed using an interest rate of 5.63%. Barging costs were based on disposal of 93 tons of dry sludge per day with a round trip of over 300 miles(449).

Philadelphia evaluated 14 different methods, or combinations of methods, for disposal of digested, secondary sludge from their

Northeast sewage treatment plant. A cost comparison of the six major sludge disposal techniques is as follows(442, 447):

| Proposals | $/Ton of Dry Solids |
|---|---|
| Pumping wet sludge to Southwest Lagoons | 7.23 |
| Barging wet sludge to sea - 10% solids | 8.78 |
| Barging wet sludge to sea - 5% solids | 11.81 |
| Trucking wet sludge to Southwest Lagoons - 10% solids | 12.05 |
| Excavating lagoons at intervals - trucking 18% solids to Southwest | 12.67 |
| Trucking wet sludge to Southwest Lagoons - 5% solids | 17.64 |
| Trucking sludge cake to Southwest | 18.90 |
| Dewatering and Incinerating Sludge | 28.01 |

While lagooning had the lowest cost, it was not selected because of the high price of land and the uncertainty of future operations. Cost estimates were calculated on the basis of 30 year bonds at 3.5% interest. The thickened sludge would be dumped in an area requiring round-trip barge travel of 227 miles.

The Washington, D. C. Department of Sanitary Engineering had studied possible future sludge disposal costs at the Blue Plains treatment plant. Estimated unit costs for 1970 are(450):

| Sludge Concentration % Suspended Solids | Barging $/Ton | Incineration $/Ton | Drying Raw Activated Sludge + Barging Digested Primary Sludge | Wet Oxidation $/Ton |
|---|---|---|---|---|
| 7.5% | $17.95/T | - | -- | $38.95(Raw Sludge) |
| - | - | $25.25/T | $27.95/T | - |
| 4.0% | $20.75/T | - | - | $31.90(Digested Sludge) |

Above costs are based on dry solids and include thickening, digestion, elutriation, vacuum filtration, and, as may be applicable, final disposal. Capital costs for new facilities were computed at an interest and amortization rate of 5.8% (capital costs for existing facilities are not included). Barging costs were based on a round trip of 400 miles, a requirement for channel dredging at the plant, and the construction of a dock.

A solids handling and disposal study completed for Camden, New Jersey, concluded that barging of sludge rather than vacuum filtration and dewatering would save $200,000 over a 5-year period(450a). Current filtration and incineration costs were $20 to $28 per ton. It was assumed that present filtration and incineration equipment would be overhauled or replaced during the next 5 years. Also, ash lagoons would have to be constructed. Barging costs were based on the disposal of a 7 percent stored, primary sludge at a round trip distance greater than 200 miles.

In general, ocean dilution is the cheapest method of sludge disposal for cities near seacoasts. Disposal through a pipeline is less expensive than barging unless very long outfalls are required. Capital and operating costs for pipeline disposal would generally be $5 per ton or less, while barging costs have been reported to be $5 to $25 per dry ton. As the data show, barging costs are a function of the distance the barge must travel to a safe disposal area.

Summary - Ocean disposal of sludge has a number of advantages for seacoast cities when compared with other disposal methods:

1. The removal of sludge from the treatment plant is complete, not even an ash residue remains.
2. Disposal of sludge at sea is relatively inexpensive.
3. Ocean disposal permits nuisance-free sludge handling assuming the sludge is digested.
4. Ocean disposal permits flexibility in plant operation, assuming once again the sludge is digested. There are few problems with sludge-volume fluctuations and the dumping schedule can be varied.

Ocean disposal of sludge lessens the effectiveness of sewage treatment, but it is being accomplished without any significant, known, detrimental effects to the receiving water that might impair the beneficial uses of the water. Long term effects are not known, so continuous surveillance is needed. While much research has been conducted by

California engineers and scientists, they recommended the following additional investigations(446).

1. Detailed monitoring of the area near ocean outfalls for physical, chemical, and biological factors.
2. Studies of bacterial viability in sea water.
3. Effects of wind and waves on the dispersion of a seawater-sludge mixture.
4. Evaluation of water standards for bathing.
5. Grease and coliform bacteria factors in sludge disposal.

Before a decision is made to use the sea for dilution, beneficial uses of the water should be evaluated with the biologic, geologic, and oceanographic characteristics of the disposal area. Then, decisions can be made concerning the degree of sludge treatment required and the best location for outfalls or barging dumps. Once adopted, a control method is required to insure that the sludge is being dumped in the prescribed location.

The disposal of sludge to the ocean will become more common in the next few years at cities located near seacoasts because it is simple, final, and less expensive than other methods. Ocean disposal, however, may not always be acceptable to the public and regulatory agencies. In the future, a decision could be made to eliminate this practice based on esthetic, scientific, or other reasons.

## 13. UNDERGROUND DISPOSAL

General - Industrial wastewaters have been disposed of underground through deep injection wells for many years--why not sludge? Economic analyses indicate that underground disposal could cost at least one-half that of conventional sludge disposal techniques, if subsurface strata would accept the high concentration of suspended solids in sludge.

Koenig reported on ultimate disposal of well treated wastewater into subsurface strata that contain natural and man-made cavities(55) such as caves, depleted mines and wells. His report indicated that subsurface disposal is very competitive with other forms of disposal.

There are several problems in addition to suspended solids, that are associated with subsurface disposal. First, the filling of natural caverns, depleted mines, or wells is specifically legislated against in a number of States(74). Second, finding sites that are geologically and legally acceptable can be a problem. Excavating underground sites for sludge disposal is very costly, and the material removed presents a disposal problem in itself. Koenig suggested nuclear blasting(55). A consideration is whether devices of sufficient size could be detonated close enough to population centers to produce caverns, economically usable for sludge disposal.

Summary - Assuming that man-made cavities, specifically created for disposal, are eliminated due to the high cost involved, subsurface disposal is limited then to natural cavities and deep-well injection into a suitable subsurface strata. Mineral production in the United States creates 152 million gallons per day of underground cavity capacity. About 116 million gpd of this total exist as bituminous coal cavities, this is significant because their distribution is relatively near the urban areas creating waste solids(55).

As Wirts proposed, sludge could be transported to underground cavities by pipelines(432). Koenig estimated the cost of pipelining waste from advanced waste treatment processes as(55):

| | 1961 |
|---|---|
| 10 miles | $0.56/1,000 gals. |
| 100 miles | $3.90/1,000 gals. |

Assuming a 5 percent sewage sludge, the 1966 costs could be $2.50 to $3.50 per ton of dry solids for 10 miles and $15 to $22 per ton for 100 miles. Koenig's figures were not based on sewage sludge so the accuracy of these estimates is questionable.

A subsurface disposal cavity should be below the level from which ground water is pumped. If this is not possible the cavity must be sealed permanently against seepage. This would be difficult and costly. The problem of acid mine drainage from bituminous coal mines is a good example of the seriousness of surface and ground water pollution. Any cavity considered for sludge disposal must be thoroughly studied and monitored to determine such factors as elevations relative to ground water, permeability of the formation, and its ability to be sealed.

Sludge disposal by deep-well injection could be much cheaper than conventional sludge handling methods. But, this technique depends on suitable subsurface geology and the approval of governmental regulatory agencies. It can be accomplished successfully as demonstrated by the fact that The Dow Chemical Company disposes of waste activated sludge in this fashion(74) at one of their large production facilities. Lowes reported that the economics of sludge handling and disposal at Dow were considerably improved by separating the difficult-to-dewater activated sludge from the primary sludge and pumping the activated sludge underground.

Deep-well injection costs are influenced by several parameters such as: (1) volume of material to be injected, (2) well depth, (3) well head pressure (affected by physical and chemical characteristics of the formation), (4) sludge concentration, and (5) required surface treatment. The surface treatment required depends on the nature of the receiving formation and the nature of the sludge to be injected. Accurate costs for subsurface disposal were not available when this report was written. Koenig estimated that the average cost of drilling oil and gas wells (5,991 ft. to 7,500 ft. deep) was $100 per foot(55).

Underground disposal of all types of sludge should be considered where the geology and legal environment are favorable. It can be less expensive than conventional disposal schemes even if the sludge must be transported long distances by pipeline to a suitable disposal area. However, because permanent contamination of water supplies can occur, extensive preliminary studies of subsurface geology are necessary as is surveillance after the system is completed.

## 14. SLUDGE DEWATERING

The primary objective of any dewatering operation is to reduce the sludge moisture content to a degree which allows ultimate disposal by incineration, landfilling, heat drying, or other means. Dewatering differs from sludge thickening in that the sludge is processed into a non-fluid form.

This chapter discusses the following dewatering processes: (1) vacuum filtration, (2) pressure filtration, (3) centrifugation, (4) sand bed drying, and (5) screening.

### A. Vacuum Filtration

General - Vacuum filtration of process-industry slurries has been in common use in Europe and the U.S.A. for many years. The process has also been used in the sewage treatment field; Milwaukee and Chicago initiated vacuum filtration more than 35 years ago(53). After World War II the popularity of vacuum filters decreased. Surveys revealed that many installations were abandoned between 1945 and 1960 due to maintenance and operational problems as well as increasing labor, equipment, and chemical costs(151).

Since 1960, however, the popularity of vacuum filtration has increased for a number of reasons that include: (1) development of self-cleaning filter media, (2) increased cost of alternative sludge dewatering methods, and (3) the increased acceptance of sludge incineration as a final disposal technique. At one time vacuum filters were not considered for sewage treatment plants serving less than 25,000 persons. Today, they are considered in economic studies and adopted for cities serving 10,000 persons or less. It was recently estimated that 1,300 vacuum filters have been installed in sewage treatment plants(251).

Mechanical dewatering by vacuum filters is applicable to all types of sewage sludge and to many industrial wastewater sludges. Centrifuges are becoming increasingly competitive with filters. But, they will not in the foreseeable future completely replace filters because they capture fewer solids and, in general, are less efficient for dewatering certain difficult biological and industrial waste sludges.

Theory and Parameters - Filtration has been defined by Hubbell as a "Process of separating solids from a liquid by passing the liquid through a porous medium on which the solids remain to form a cake"(65). In rotary-drum vacuum filtration the drum is continuously passed through the sludge where it picks up solids to form a cake which is partially dewatered and discharged. Figure 14.I shows a typical installation. The filter is a cylindrical drum with some filter media covering the outside surface. Internally, the drum is divided into drainage compartments which connect to the filtrate system. About 20 to 40 percent of the drum is submerged in the filter "pan" containing the sludge as the drum is rotated. A sludge mat is formed on the filter media as a result of a vacuum (10 to 26 inches Hg) applied to the drainage compartments servicing this submerged portion(6). As the mat, or cake, rotates out of submergence, vacuum and dewatering are continued. The cake is removed from the drum just before it would be submerged in the pan once again.

Disc type vacuum filters are sometimes used for dewatering industrial slurries. They are particularly conducive to filtering large volumes of easily dewatered solids.

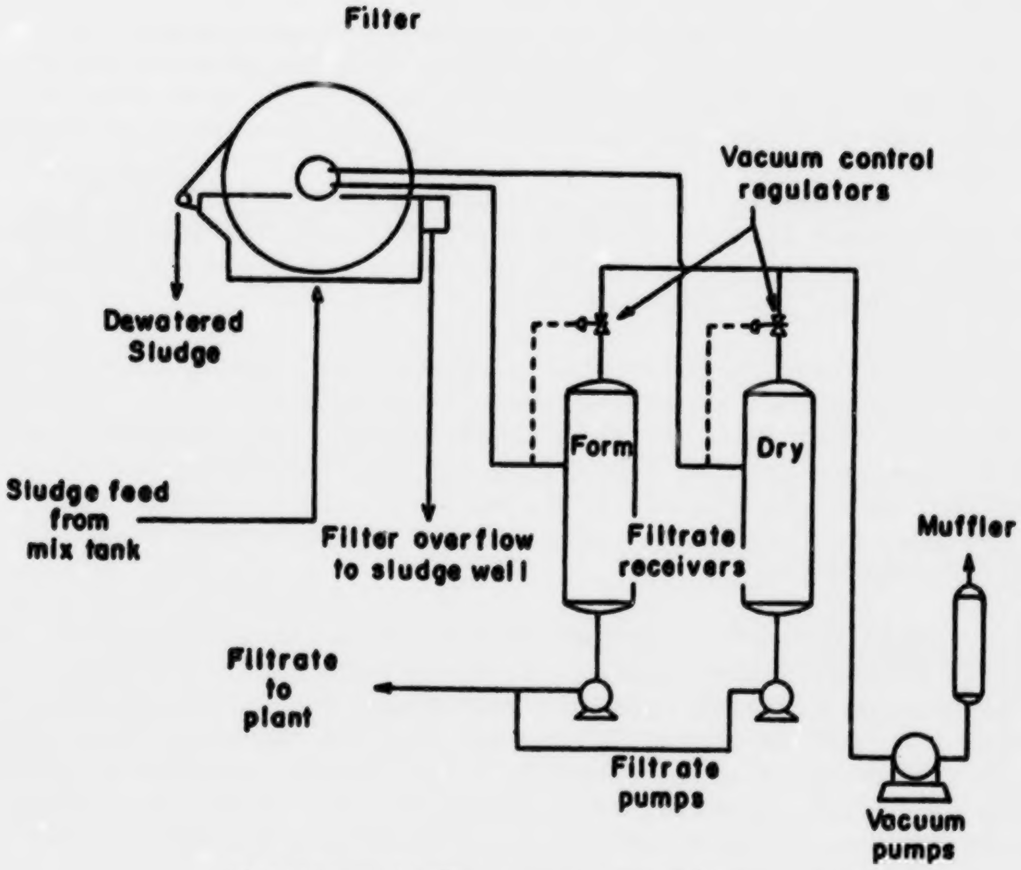
Rich described vacuum filtration as a special case of flow through a bed of solids(6). He stated that permeability through the solids depended on cake characteristics such as porosity, average specific surface area of the cake particles, and sludge compressibility. Resistance to filtration is effected by the filter media and by the filter cake. A number of sludge and operating variables affect the filtration performance.

Sludge Variables - Factors that affect the ability to dewater sludge are: (1) solids concentration; (2) sludge age and temperature; (3) sludge and filtrate (liquid) viscosity; (4) sludge compressibility; (5) chemical composition; and (6) the nature of the sludge solids including volatile content, size, shape, electrical charge of the particles, density, ratio of slimes to coarse particles, content of "bound" water and whether or not the sludge has been exposed to biological treatment.

Operating Variables - (1) Vacuum, (2) amount of drum submergence, (3) drum speed, (4) degree of agitation, (5) filter media, and (6) conditioning of the sludge prior to filtration, all affect the operation of vacuum filtration equipment.

Increased solids concentration in the filter feed increases filter production (yield). In general, the sludge filtration rates increase directly in proportion to the increase in feed sludge-solids concentration; a smaller filtrate volume has to be removed per pound of filter-cake formed. There is, however, a practical upper limit (probably 8 to 10 percent solids for sewage sludge) which, when exceeded, makes chemical conditioning and sludge distribution difficult. Figure 14.II illustrates the improved

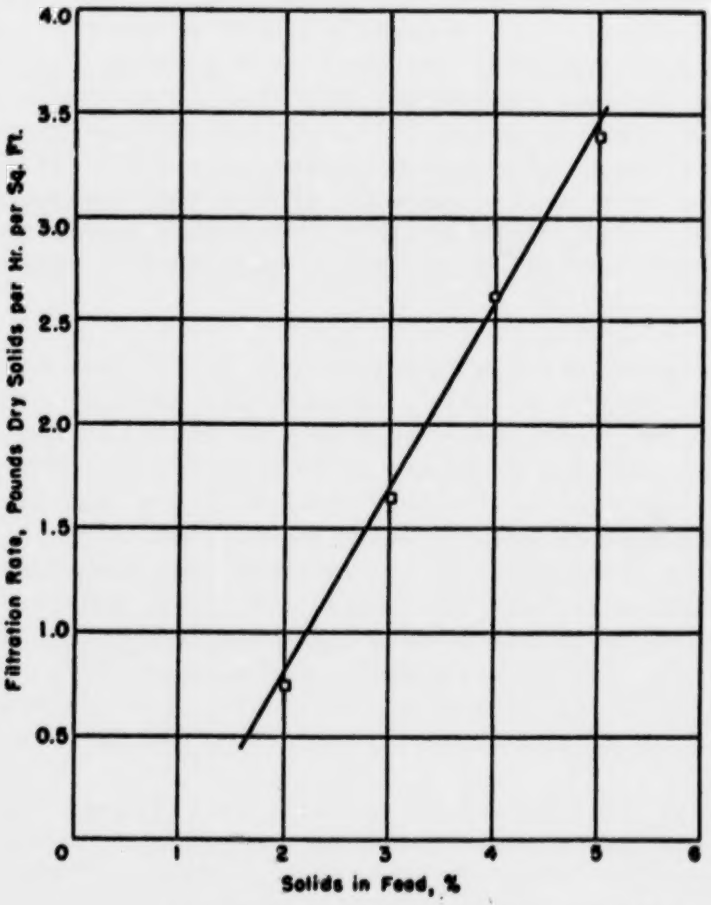
Figure 14.I


Filter
Vacuum control regulators
Dewatered Sludge
Form
Dry
Sludge feed from mix tank
Filter overflow to sludge well
Filtrate receivers
Muffler
Filtrate to plant
Filtrate pumps
Vacuum pumps

Piping layout for filter vacuum system with vacuum filtration.

(Reprinted by permission from Vol. 28, No. 12, p. 1451, December 1956, Sewage and Industrial Wastes)

Figure 14.II



Filtration rate versus solids concentration

(Reprinted by permission from Vol. 28, No. 12, p. 1449, December 1956, Sewage and Industrial Wastes)

filter rates possible with increased feed solids concentration for a primary-activated sewage sludge mixture(232).

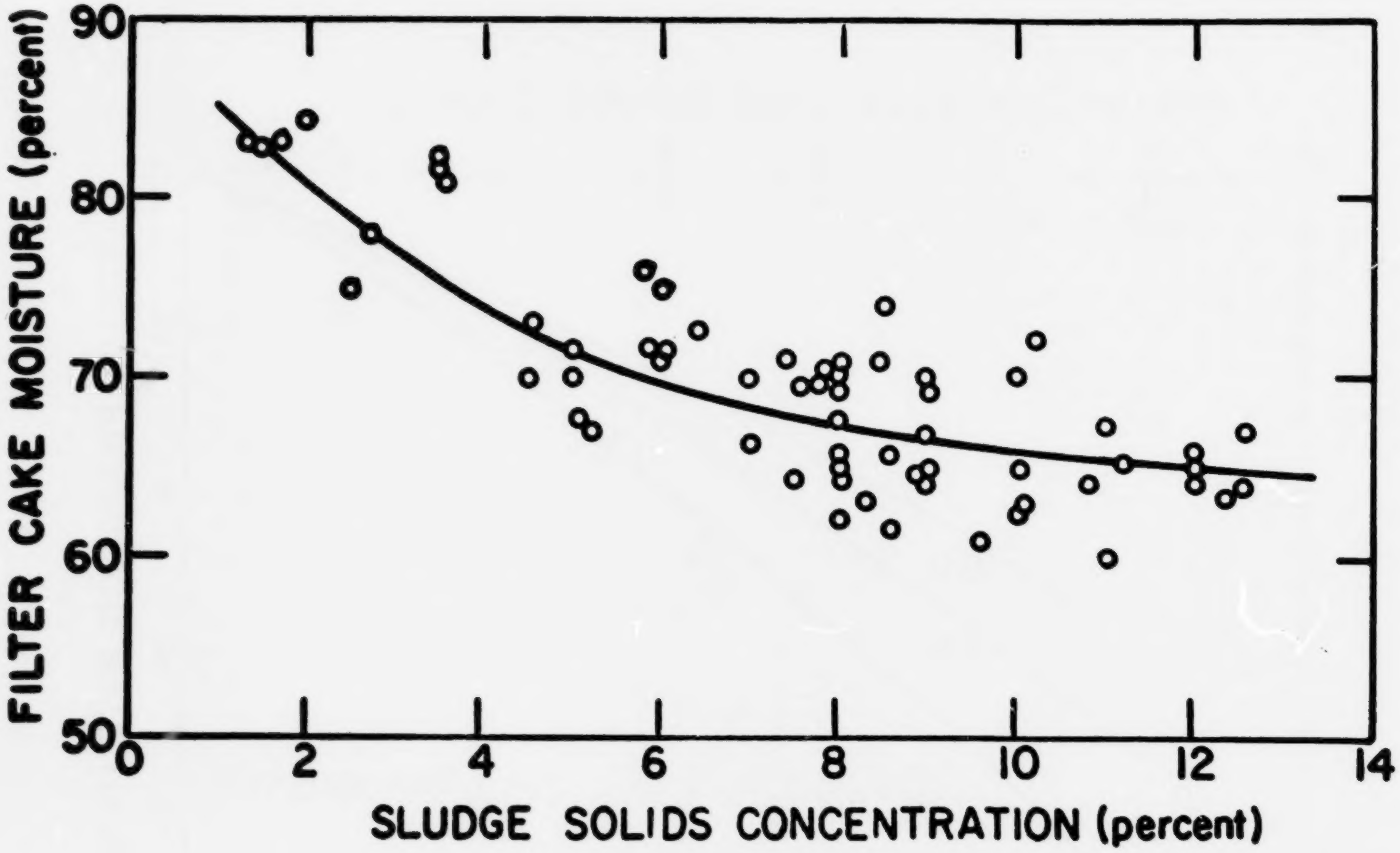
Other advantages of increased solids concentration are that less conditioning chemicals are usually required per pound of dry solids and filter-cake moisture is reduced. These facts make a tremendous difference in operating costs at many filter installations. McCarty presented the data in Figure 14.III, which show the relation between decreasing filter-cake moisture and increasing sludge solids concentrations(61). He also described vacuum filtration rates in terms of moisture removal rates. Figure 14.IV shows data averaged from many treatment plants that relate solids concentration, filter yields, and moisture removal rates. The median moisture removal rate is 4.9 gallons per square foot per hour.

Most people agree that as sludge ages, it becomes more difficult to dewater on vacuum filters. Ettelt and Kennedy observed the aging effect on filter-cake moisture using thickened activated sludge at the Chicago Sanitary District(56). Figure 14.V shows the relation between increasing cake moisture and increasing age of the thickened sludge. It also shows that freshening of sludge by re-aeration dramatically reduced the cake moisture even though the sludge had aged only 3.5 hours. Wishart and co-workers found that sludge aeration for 1 to 2 hours significantly reduced the required ferric chloride conditioning dosage(239). They theorized that this was due to decreased alkalinity and the oxidation of reducing compounds that exert a ferric chloride demand.

Up to a point, the higher the vacuum, the greater the filter yield. This relationship is shown in Figure 14.VI for a variety of sludge dewatered on pilot plant filters(232). Trubnick and Mueller questioned, however, whether vacuums in excess of 15 inches Hg significantly affect cake yields and moisture(227). It seems that the importance of increasing the vacuum beyond this point depends on the sludge cake compressibility and the filter media. An ideal vacuum filter design would incorporate two independent vacuum systems; one operating while the cake is being formed, and the other after it comes out of submergence and is being dried. With very compressible cakes, a moderate forming vacuum may be desirable to prevent media plugging. However, maximum drying vacuum is almost always desirable to produce a cake having a minimum moisture content.

Drum submergence and drum speed influence the filter yield and filter-cake moisture. Increasing the drum submergence increases the detention period of the form cycle, thereby generally resulting

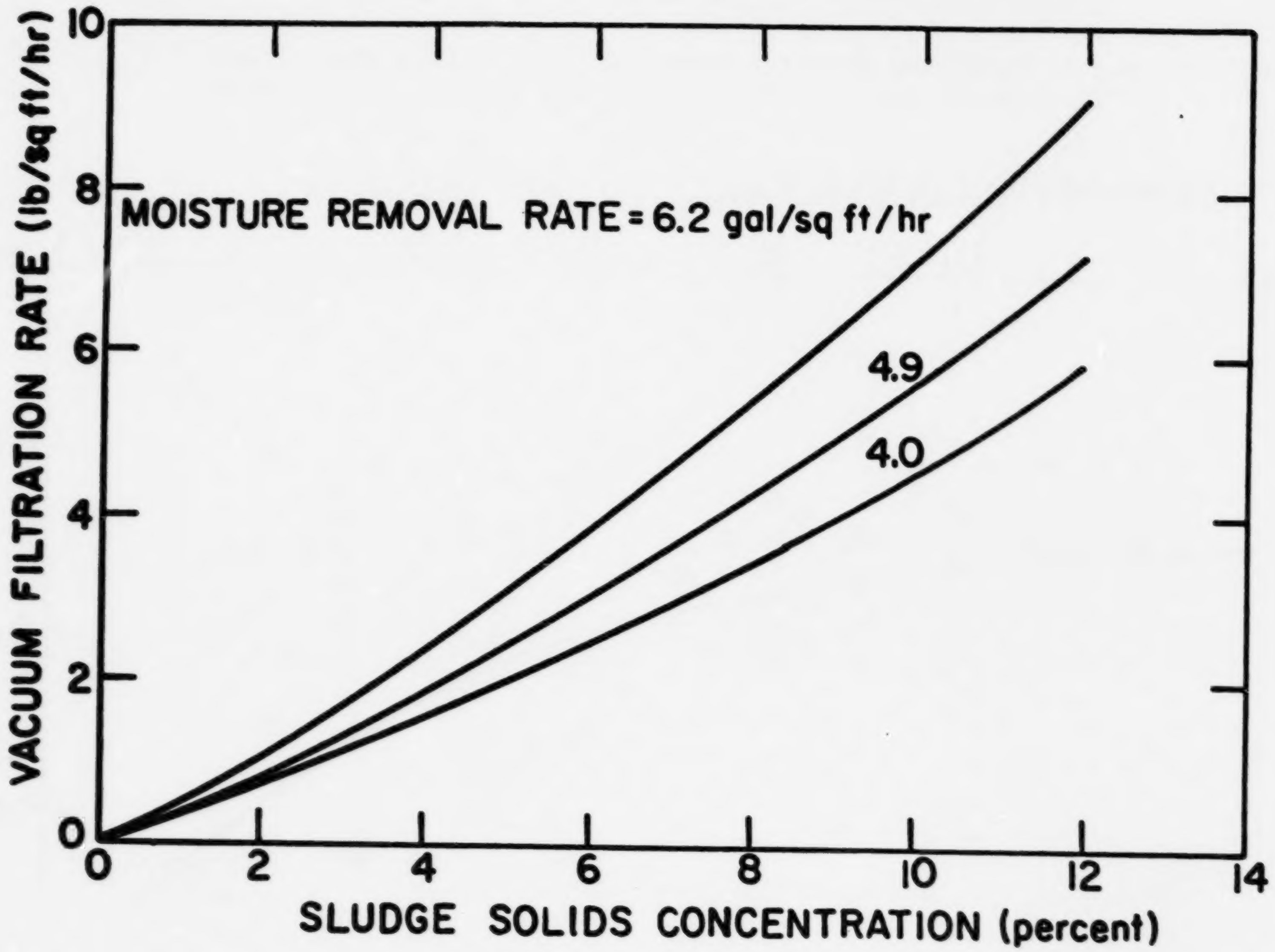
Figure 14.III



Relationship Between Average Sludge Solids Concentration and Vacuum Filter Cake Moisture Content Reported by Various Plants.

(Courtesy P. L. McCarty, Stanford University)

Figure 14.IV



Relationsip Between Sludge Solids Concentration and Dry Solids Vacuum Filtration Rate for Various Moisture Removal Rates

(Courtesy P. L. McCarty, Stanford University)

**Figure 14.V** EXAMPLE OF EFFECT ON CAKE MOISTURE OF ELAPSED TIME AFTER THICKENING SLUDGE. (1.12% ACTIVATED SOLIDS)

(Reprinted by permission from Vol. 38, No. 2, p. 256, Feb. 1966, J. Water Pollution Control Federation)

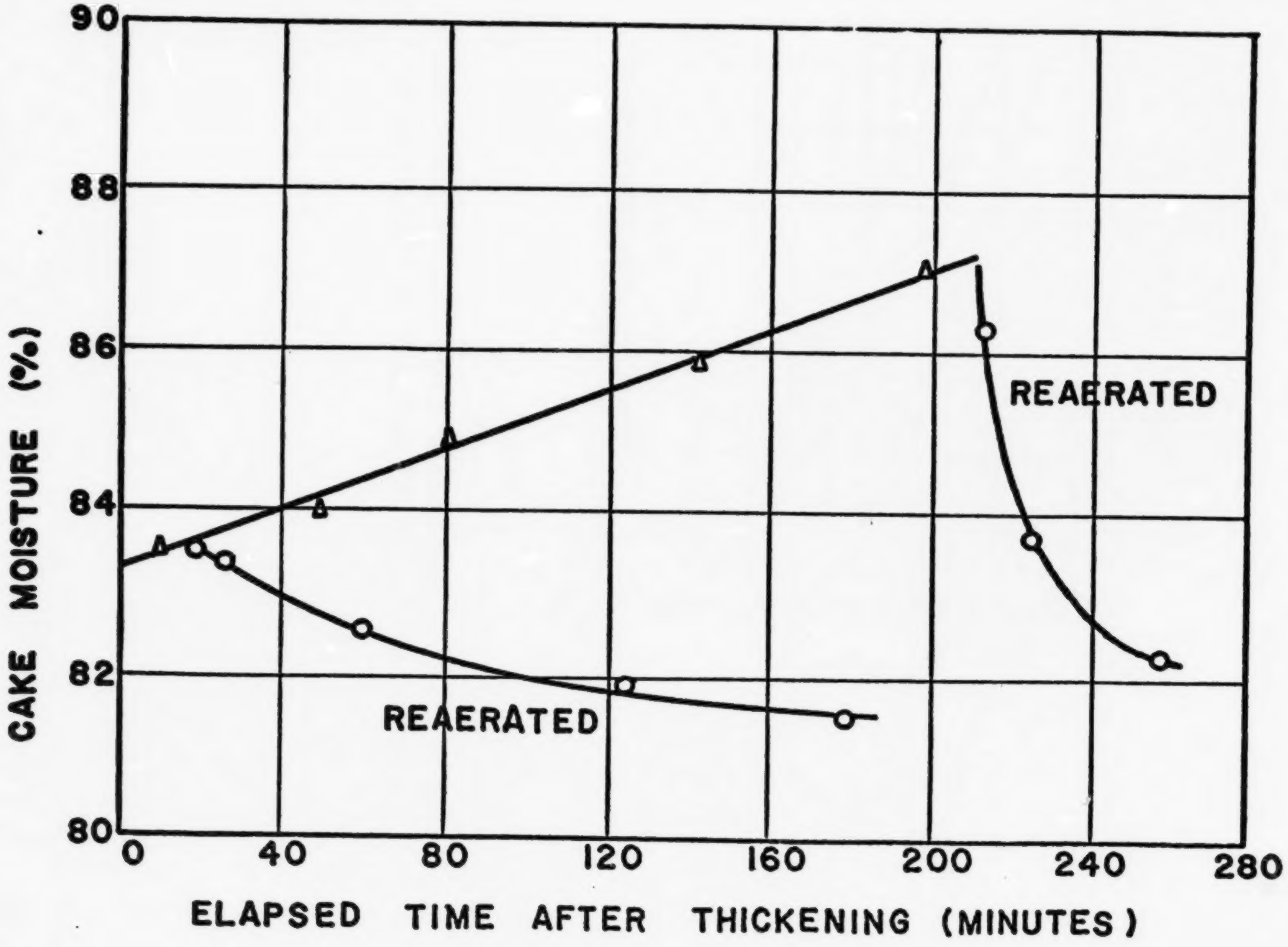
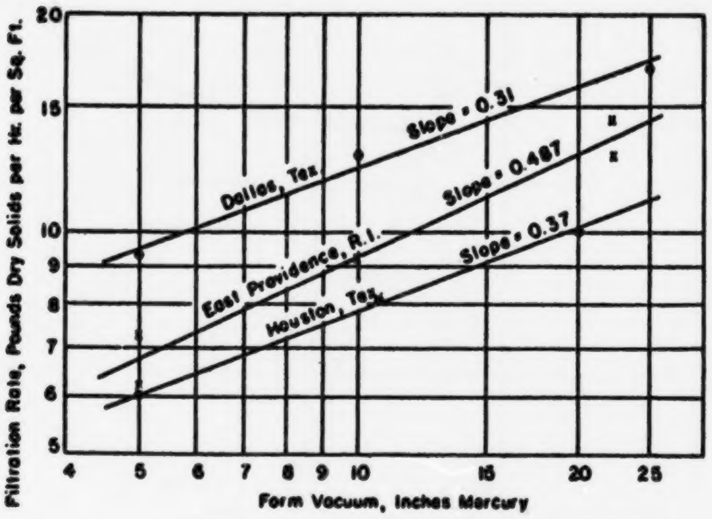


Figure 14.VI



**Filtration rate versus form vacuum; pilot-plant data.**

(Reprinted by permission from Vol. 28, No. 12, p. 1456, December 1956, Sewage and Industrial Wastes)

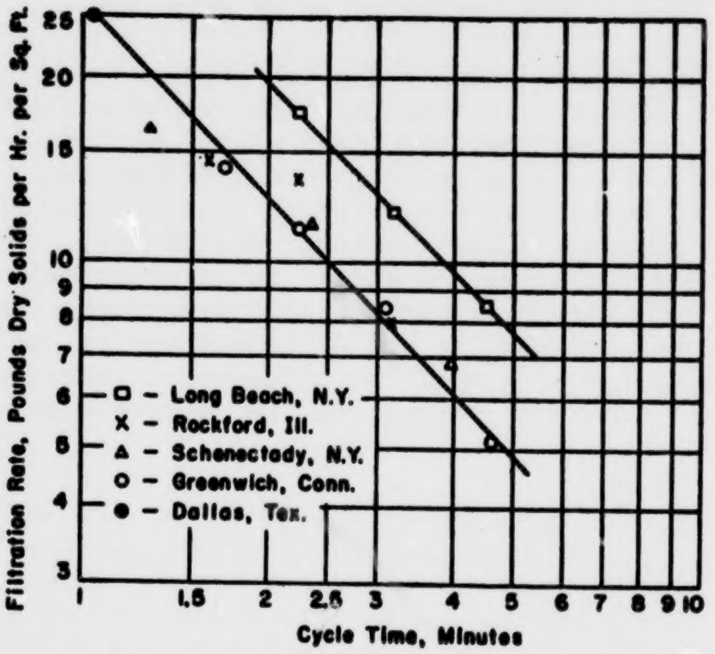
in a thicker cake or increased filter yield, but often a higher cake moisture. Increasing the filter cycle time (or slowing the speed) would, as expected, decrease the yield or production rate. This parameter is described in Figure 14.VII for a number of different sewage sludges. While yield may be sacrificed, increasing the cycle time can be expected to decrease the filter-cake moisture because the drying cycle is extended.

Agitation of the sludge during and after chemical conditioning is an important operating parameter. The proper evaluation of this parameter requires variable-speed mixing equipment for chemical conditioning tanks and the vacuum filter pan. When being mixed with chemicals, some sludges require more violent agitation than others. After chemical conditioning, the general rule is to handle the sludge as gently as is practical. This usually means only enough filter pan agitation to prevent solids classification and to keep the solids in suspension and well distributed along the length of the filter pan. Because sludge viscosities vary, optimum control requires variable speed pan agitation equipment.

Proper selection of the vacuum filter media is very important to efficient filter performance. Early filter installations were limited in media selection, but now a wide variety is available including natural and synthetic fabrics, metal coils, and flat metal belts. Sludge characteristics and chemical conditioning play an important part in media selection. So, the selection should be based as nearly as possible on actual plant conditions, using a laboratory filter leaf test or by the reaction of different media panels on an operating filter(66). In general, a media is selected on the basis of the cleanest filtrate consistent with high filtration rates and reasonable replacement costs.

Most raw primary sewage sludges and certain industrial waste sludges have fibrous and non-uniform solids. Vacuum filtration of these solids is most efficient with media having comparatively large openings that do not clog or "blind" with sludge particles. Media blinding leads to lower filter yields, increased chemical consumption, and the need for frequent media washing. Increased filtrate solids is one disadvantage associated with "open" media, but often these solids easily resettle when returned to primary clarifiers. In some evaluations of raw sludge dewatering after polymeric flocculent conditioning, practical vacuum filtration was not possible until open media was substituted for "tight" media.

Figure 14.VII



Filtration rate versus cycle time; pilot-plant data; primary-digested sludges; form vacuum, 20 to 25 in. Hg; submergence, 25 per cent.

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The nature of the sludge to be filtered is an important filtration parameter, but sometimes its modification is limited as so many characteristics vary with the sludge source and methods of treatment(66). In general, raw sludge is easier to filter than digested sludges, and primary sludge is easier to filter than secondary sludges. Sludge particle size, shape, electrical charge and density affect filter-ability because they affect compaction and flocculating chemical demand. For example, small particles (fines) tend to form a compact mat under vacuum which leaves a small void ratio for passage of the liquid(227). Small particles also exert a greater chemical flocculent demand per unit weight than large particles. Genter reported that small particles have a greater surface attraction for water than large particles. If solids have a low specific gravity, the wetting effect is increased(21). Usually the larger the particle size is, the higher the filter rate (in dry pounds per square foot), and the lower the cake moisture. An increase in slimes or extremely fine particles decreases the filtration rate and increases the cake moisture.

Compressible sludge solids tend to deform as pressure increases and the result is a tight filter-cake that resists liquid separation. According to Genter, compressibility of sludge solids is a direct function of the volatile content(21). Many operators have noticed increased chemical consumption with increased sludge volatile content. The structure of the solids and their tendency to deform can be controlled in part by chemical conditioning.

The chemical composition of a sludge has a large influence on the requirement for chemical flocculents. Genter believed that the total flocculent demand is the sum of the liquid and solids demand(21). The liquid demand is thought to be from the alkalinity of the sludge, and it is particularly important in digested sludge because of the bicarbonate alkalinity formed during the digestion process. The solids demand is proportional to the ratio of volatiles to inerts. Digestion reduces this ratio but increases the alkalinity in the process. (For additional details, see the Elutriation chapter).

Chemical conditioning is usually a necessary step before sludge vacuum filtration. It enhances maximum efficiency of sludge dewatering. Only a few sewage sludges do not require it. Some industrial sludges can be filtered without chemical treatment but they often have, due to process requirements, a high composition of the same chemicals normally used to condition sludges. Chemical flocculents agglomerate solids and cause a release of water. By doing so, they create large uniform voids in the sludge so water can pass through. Genter believed chemicals to be the simplest and most effective way of keeping void channels relatively open before and during vacuum filtration(240).

A wide variety of chemicals have been evaluated for conditioning sludges prior to vacuum filtration(195). The list includes the following: ferric chloride, ferrous chloride, ferric sulfate, ferrous sulfate, sulfuric acid, nitric acid, hydrochloric acid, lime, sodium dichromate, chromic chloride, aluminum chloride, aluminum chlorohydrate, zinc chloride, titanium tetrachloride, chlorine, sodium chloride, potassium permanganate, cupric chloride, soap, aluminum sulfate, sulfur dioxide, phosphoric acid, dicalcium phosphate, and organic polyelectrolytes.

Physical filter aids used along or in conjunction with chemicals to increase porosity and filtration rates include: coke, bone ash, peat, paper pulp, ground blast furnace slag, diatomaceous earth, ground garbage, fly ash, clay, sawdust, crushed coal, animal blood and activated carbon.

In this country the most popular chemical conditioning materials are ferric chloride, lime and cationic polyelectrolytes. Overseas, aluminum chlorohydrate is a common flocculating agent along with lime and ferric salts. Often combinations of ferric salts and lime are used to optimize chemical conditioning costs. The dual use of anionic and cationic polymers has been very successful because of the two basic phenomena thought to be involved with flocculation--charge neutralization and particle bridging (or agglomeration). The first function is performed by the cationic materials; the second by the anionic materials.

The success of synthetic polymeric flocculents represents one of the few recent major advances in the sludge handling field. These materials have captured the major portion of the municipal sludge conditioning market, exclusive of raw waste activated sludge.

To a point, increased chemical dosages increase the vacuum filter yield and decrease the cake moisture. A typical curve relating dosage and filter yield is presented in Figure 14.VIII(232). As indicated, a dosage is reached where additional yield increases are not achieved. The curves in Figure 14.VIII show a plateauing of the yield, but yields may decrease drastically from overdosing.

Ferric salts and lime added to raw sewage sludge will change the pH and decrease the microorganism population. This is important for odor control, but the reduction is not sufficient to eliminate public health hazards from improper use of filter-cake. Figure 14.IX shows a substantial reduction in coliform MPN, but the sludge could not be called sterilized. Organic polymeric flocculents do not affect the coliforms in the filter-cake.

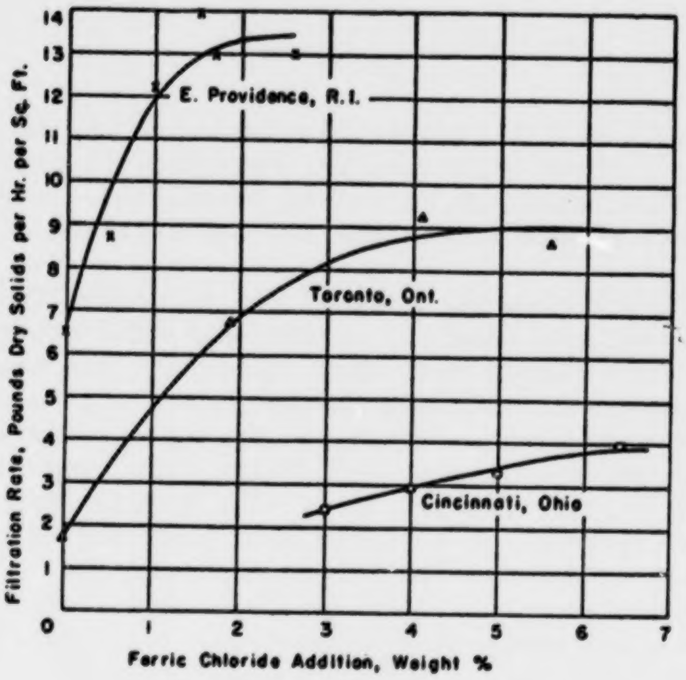
Beck and co-workers developed a Buchner funnel laboratory test to evaluate chemical conditioning and other parameters(236). It is a simple test that indicates: the best flocculent(s) for a particular sludge, the optimum sludge and flocculent dilution, the best sludge-flocculent mixing procedures, the effect of system vacuum, sludge age, and drying time, and allows an estimate of the filter-cake moisture. The Buchner funnel test has certain limitations, so a filter leaf test and/or pilot filter runs should be considered. Testing on a filter leaf permits fairly accurate predictions of filter yields, the best filter media, cake moisture, cake discharge characteristics, and necessary media maintenance.

Coackley and Jones modified the Buchner funnel test so they could compare filtration resistance for different types of sludge. They compared sludge dewatering characteristics by developing a specific resistance value: it was defined as the pressure difference required to produce a unit rate of flow of filtrate having a unit viscosity through a unit weight of cake. For any conditioned sludge and filter vacuum, tests can determine the specific resistance of the sludge(233). The test is useful for comparing different prefiltration procedures and flocculents. Laboratory tests can be applied to full-scale design and operation along with filter leaf and/or pilot filter tests.

Design and Operation - Vacuum filter systems are designed from data showing quantities of sludge to be filtered, sludge characteristics, filtration rates, cake moisture, and filter operation cycles(66). As discussed previously, this data could be generated from laboratory or pilot filter tests on the sludge. If the actual sludge to be filtered is not available, vacuum filter systems are designed using averaged data from plants treating sludge with similar characteristics.

Yield or production rate is the basic factor in sizing vacuum filter installations. A conservative design rate of 3.5 pounds per square foot per hour has been widely used(65c), but a more accurate rule-of-thumb is to assume that the yield is equal to the solids concentration of the sludge to be filtered. In general, this means the yield may vary from 2 to 10 pounds per square foot per hour. The low values represent filtration of fresh and digested activated sludge; the high values are typical for raw primary, or primary plus trickling filter humus, sludge filtration.

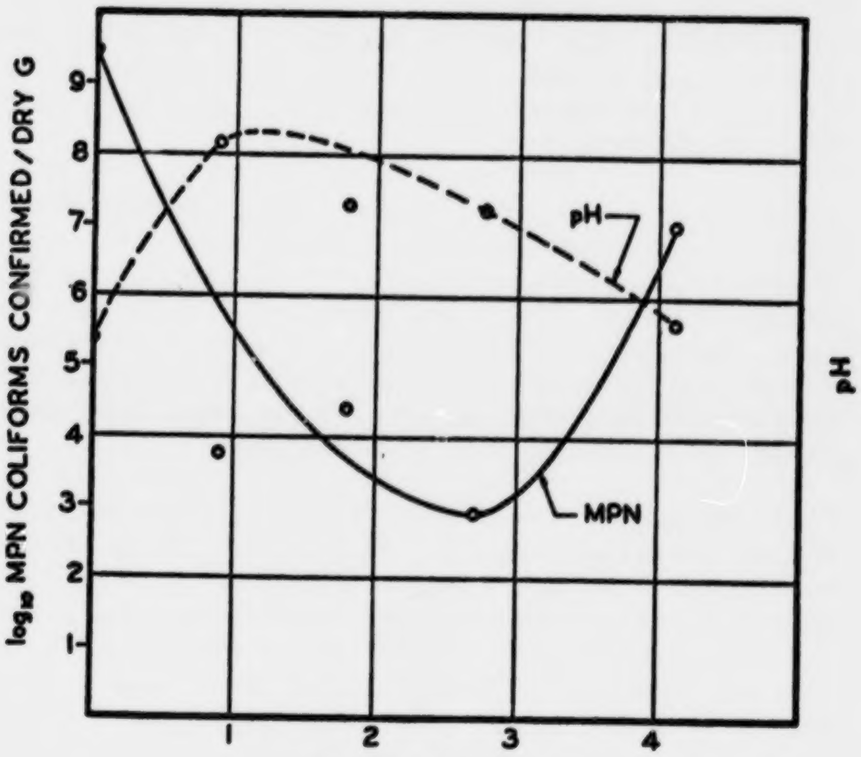
Figure 14.VIII



Filtration rate versus ferric chloride addition—pilot-plant data

(Reprinted by permission from Vol. 28, No. 12, p. 1457, December 1956, Sewage and Industrial Wastes)

Figure 14.IX



Effect of ferric chloride dosage on coliform count in dewatered fresh sludge.

(Reprinted by permission from Vol. 30, No. 11, p. 1373, November 1958, Sewage and Industrial Wastes)

Vacuum filtration facilities are generally sold as a package by filter manufacturers. In addition to the filter itself the package normally includes vacuum pumps, sludge feed pumps, filtrate pumps, sludge conditioning tanks, chemical feed pumps, and belt conveyors to transport dewatered filter-cake. Except for cake conveyors, an optimum design includes complete individual accessories for each vacuum filter(251). This enhances operational flexibility and reduces the opporutnity for hydraulic inbalance.

Because it is difficult to predict exactly the performance of vacuum filters before installation, a maximum amount of flexibility consistent with reasonable economy should be designed into the system. An optimum design would incorporate the following features:

1. Separate chemical conditioning tanks having two mixing stages: (a) a flash mix variable from 100 to 1000 rpm, and (b) a slow mix variable from 10 to 100 rpm. Variable detention periods for each stage is desirable. The tanks should be open so the filter operator can observe the effect of the chemical additives, and it should be possible to change the chemical addition point(65c). Sludge and additives should be mixed with agitation that produces the best floc and at minimum chemical dosage. Conditioning tanks should be adjacent to the filter and have flume discharges over the lip of the filter pan to broadly distribute the treated sludge. Filtering sludge as soon as possible after chemical conditioning is desirable.

2. Sludge and chemical dilution facilities. Each sludge has an optimum solids concentration for filtration. If the feed sludge has a high solids concentration it may, therefore, be desirable to add dilution water. Chemical flocculents are often more efficient if diluted so adequate water lines should be provided for this operation.

3. Variable speed filter pan agitator drives. The stability of sludges and their need for agitation in the pan varies, so flexibility in the agitation speed is very desirable.

4. Delivery of a uniform sludge feed.

5. Effective filter media cleaning facilities.

6. Convenient means of positioning the internal bridges that control the point of cake pick-up, drying and discharge.

One interesting design modification discussed by Emmett and Dahlstrom is the top feed filter(245). In this unit, cake formation occurs with gravity rather than against it as is the case with conventional rotary drum filters. The use of top feed filters is dictated by the feed solids size distribution and the rate of cake formation. There is no limitation on larger particle sizes, but the solids should contain no more than 30 percent of material passing a 200 mesh and only very small quantities of 5-micron-diameter particles. A one-inch cake should be formed in 10 seconds or less.

Top feed filters are not used for dewatering sewage sludges and they are used infrequently to dewater industrial sludges because: (1) they are more expensive per ton of solids processed than other filters, (2) there is a lack of understanding of the basic phenomena, and (3) there is a need for improved engineering design. The concept of top feed filtration is good; hopefully, the design will be improved.

The primary goals in the operation of vacuum filters usually are to attain high filter yields and minimum cake moistures(66). These goals generally require that the following important design and operating parameters be observed:

1. Provide a thick, feed sludge.
2. Effectively condition the feed sludge.
3. Operate the vacuum filter at a minimum cycle time consistent with adequate cake discharge and desired cake moisture.
4. Operate the filter with a maximum drying vacuum.
5. Operate the filter with low submergence.
6. Prevent media blinding.

In some cases, the highest yields and lowest cake moistures may not be the most economical or reasonable way to operate. Depending on the method of ultimate cake disposal, other goals may be more reasonable. Each vacuum filter operator must decide on the particular goals appropriate to his plant.

Because filtration is more of an art than a science, it is desirable to have well-trained filter operators. It is possible to substitute excessive chemical dosages for close control of the filtration operation, but this is uneconomical; chemical costs may account for 50 percent of the total vacuum filter operating expense. Filter operations should never be considered as having reached the ultimate in performance because new refinements in techniques such as dilution, agitation, and chemical treatment allow process improvements.

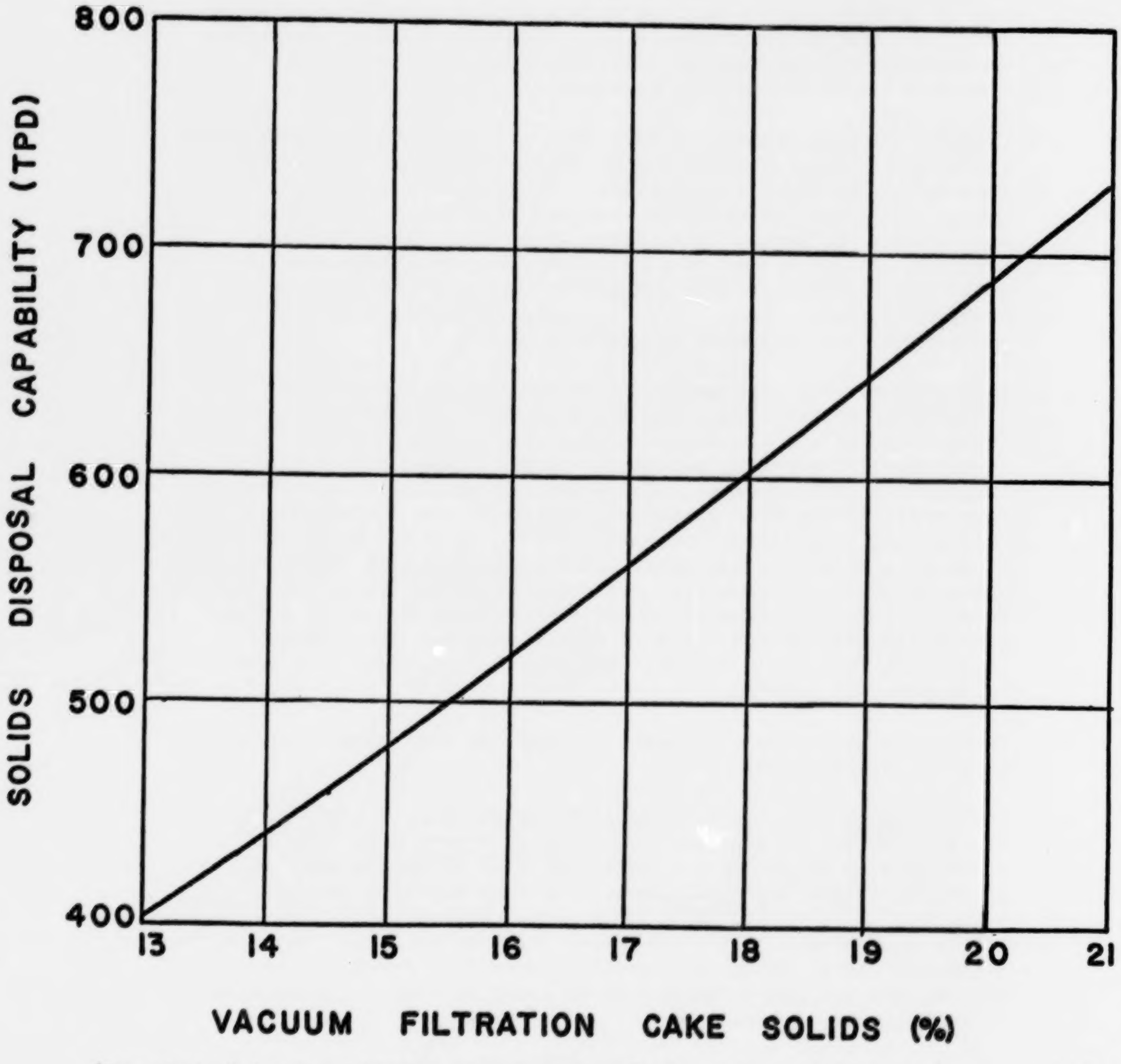
Filtered digested sludge is used as a soil conditioner on farmland and public parks. It also may be incinerated, heat-dried, composted, or deposited in landfills. The disposal of filtered raw sewage sludge is not quite as simple. It often is heat-dried, incinerated, or buried in sanitary landfills. Some filtered sewage sludge is dumped on public land, but this procedure is risky due to possible odor and health problems from the high bacteria content. Many inorganic industrial sludges are filtered and satisfactorily dumped in landfill areas.

Performance - The performance of vacuum filters is usually measured by filter yield, the filter-cake characteristics, and the quality of the filtrate. Cake production and moisture are particularly important, especially if the sludge is ultimately incinerated or heat-dried. For example, the importance of filter-cake moisture has been emphasized by Ettelt and Kennedy for the Chicago Sanitary District operation(56). As shown in Figure 14.X, there is a direct relationship between filter-cake solids and the capacity of their flash drying plant. Note that 15 percent cake solids allows the disposal of 480 tons per day but an 18 percent cake solids allows the disposal of 610 tons per day. Vacuum filtration is subject to many variables; generalized data should be viewed with caution.

The following general and specific data are offered with only minor interpretation.

Typical yield data for a variety of sludges were listed in the design portion of this section. Cake moistures vary from 55 to 85 percent by weight depending on the type of sludge handled and the filter operating conditions. The cake moisture should be adjusted to the method of final disposal because it is inefficient to dry a cake more than is required. For example, at some treatment plants using incineration for final disposal, the filter cake has had to be wetted in order to reduce incinerator temperatures.

FIGURE 14.x-EFFECT OF DRIER FILTER CAKE ON CAPACITY OF FLASH DRYING PLANT AT CHICAGO



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Incineration of the filter-cake without the continuous use of auxiliary fuel is desirable; if possible, the filter operation should be adjusted to produce a cake sufficiently dry that fuel is not needed except for start-ups. Burial of filter-cake on the treatment plant property, however, eliminates the need for a cake with equal dryness. In many instances, the cake moisture content is controlled by discharge characteristics of filter-cake from the drum. "Wet" cakes often do not allow a clean discharge and therefore blind the media.

The concentration of total solids in the vacuum filter filtrate is the primary measure of filtrate quality. It may vary between 100 and 20,000 mg/l depending on the sludge type, the filter media, and the vacuum(65). Activated sludges, particularly when digested, contain higher proportions of fine particles than primary sludge and, therefore, produce poorer filtrates. For this reason, plants filtering activated sludge usually employ tight filter media.

Filtrate is often returned to the head of the treatment plant. While the solids in the filtrate normally resettle readily, fine solids may build up and reduce overall plant treatment efficiencies, in part due to high oxygen demand and demand for additional chemical conditioning. Filtrate solids, therefore, should be kept as low as possible, consistent with efficient filter operation. Disposal of filtrate to elutriation or thickening tanks has been investigated in the hope that any residual flocculent activity would improve basin solids capture efficiencies; varying degrees of success have been reported.

One vacuum filter manufacturer reported the following cake moisture and inorganic chemical conditioning requirement for a variety of sewage sludges(252):

| Treatment Process | Thickened Sludge Conc. (% Solids) | Chemical Requirements $FeCl_3$ (%) | Chemical Requirements CaO (%) | Cake Moisture (%) |
|---|---|---|---|---|
| Primary Settling | | | | |
| Undigested | 10 | 1.0 | 6.0 | 66 |
| Digested | 10 | 2.5 | 7.5 | 70 |
| Standard Rate Trickling Filter | | | | |
| Mixed primary & secondary | 8 | 1.5 | 7.0 | 68 |
| Digested mixture | 8 | 3.0 | 8.0 | 71 |

| Treatment Process | Thickened Sludge Conc. (% Solids) | Chemical Requirements FeCl$_3$ (%) | Chemical Requirements CaO (%) | Cake Moisture (%) |
|---|---|---|---|---|
| High-Rate Trickling Filter | | | | |
| Mixed primary & secondary | 7 | 2.0 | 8.0 | 70 |
| Digested mixture | 7 | 3.0 | 8.0 | 72 |
| Activated Sludge | | | | |
| Mixed primary & secondary | 6 | 3.5 | 5.0 | 75 |
| Digested mixture | 6 | 3.5 | 9.0 | 76 |

A review of the operating records of about 60 sewage treatment plants having used ferric salts and/or lime yielded the average data listed below(242, 244, 253):

| Type of Sludge | Chemical Dose Rate (%) Ferric Chloride | Chemical Dose Rate (%) Lime | Yield (Lbs./sq.ft./hr.) | Cake Moisture (%) |
|---|---|---|---|---|
| 1. Raw Primary | 2.1 | 8.8 | 6.9 | 69.0 |
| 2. Digested primary | 3.8 | 12.1 | 7.2 | 73.0 |
| 3. Elutriated digested primary | 3.4 | -0- | 7.5 | 69.0 |
| 4. Raw primary + filter humus | 2.6 | 11.0 | 7.1 | 75.0 |
| 5. Raw primary + activated sludge | 2.6 | 10.1 | 4.5 | 77.5 |
| 6. Raw activated sludge | 7.5 | -0- | - | 84.0 |
| 7. Digested primary + filter humus | 5.3 | 15.0 | 4.6 | 77.5 |
| 8. Digested primary + activated sludge | 5.6 | 18.6 | 4.0 | 78.5 |
| 9. Elutriated digested primary + activated sludge: | | | | |
| (a) Average w/o lime | 8.4 | -0- | 3.8 | 79.0 |
| (b) Average w/lime | 2.5 | 6.2 | 3.8 | 76.2 |

Most of the 60 locations providing the above data have changed to the use of polymeric flocculents in place of ferric salts and lime.

Interestingly, in each sludge category, digestion increased the cost of chemical treatment and increased cake moistures, while decreasing filter yields. This fact should be considered in any decision of whether to digest raw sludges.

Elutriation lowers chemical costs for digested primary sludge but not for digested secondary sludges. At secondary waste-treatment plants, elutriation often increases overall treatment costs because fine elutriated solids are recycled to other treatment processes.

Average data from the many sewage treatment plants using polymeric flocculents to condition sludges show the following(253):

| Type of Sludge | Dose Rate (%) | Yield (Lbs./sq.ft./hr.) | Cake Moisture (%) |
|---|---|---|---|
| Raw primary or raw primary and filter humus | 0.2 - 1.2 | 6 - 20 | 63 - 72 |
| Digested primary | 0.2 - 1.5 | 4 - 15 | 66 - 74 |
| Digested primary and activated | 0.5 - 2.0 | 4 - 8 | 68 - 76 |

Garber and co-workers studied vacuum filtration in great detail at the Los Angeles Hyperion Treatment Plant(180). They determined that particle size, shape, and compressibility were very important parameters in filter operation. After prolonging elutriation until most of the fines were washed out of the sludge, they obtained 30 percent greater filter yields at 80 percent of the flocculent demand.

This investigation proved the importance of particle size, but it does not offer a practical solution to vacuum filtration problems because the elutriate solids must still be disposed of in an acceptable manner. It was decided that chemical conditioning offered a better chance to improve vacuum filtration than did equipment redesign. After investigating dozens of chemical flocculating materials, the Hyperion personnel chose to condition their sludge with a combination of ferric chloride and organic polyelectrolyte. The use of the polymer increased the filter yield by 45 percent.

Sherbeck reported the following advantages upon substituting organic polymeric flocculents for ferric chloride and lime at Bay City, Michigan(182):

1. Less chemical handling equipment and space was required because the average inorganic flocculent dosage of 440 pounds per ton was replaced by an organic flocculent dose of 17 pounds per ton.
2. Less incinerator ash was produced, easing ash disposal problems (cake volatiles increased from 63 to 75 percent).
3. The vacuum filter and incinerator operating time was reduced due to the increase in filter yield from 3.1 to 6.3 pounds per square foot per hour.
4. Employee morale increased due to improved safety and cleanliness.

Thirty percent of the vacuum filter surface area was sealed off in order to prevent overloading of the incinerator as a result of increased filter yields.

Morris reported that plants in Atlanta, Georgia also converted to the use of a cationic polymer in place of ferric salts and lime(183). He summarized chemical evaluations and plant data from Atlanta as follows:

1. The conversion to polymers was simple because existing equipment could be used.
2. Laboratory Buchner funnel tests were good indicators of plant efficiency.
3. Polymer operating efficiencies were significantly affected by the feed-sludge solids concentration and alkalinity.
4. Polymers allowed exceptional production rates at only a small loss in drying efficiency.
5. Polymeric flocculents showed no corrosiveness, toxic effects, or inorganic residues and left an easily cleaned filter media and filter drum.
6. Polymer treatment resulted in a filtrate clarity equal to, or better than, that obtained under previous conditions.

The advantage of decreased handling of chemicals, provided by polymers, was emphasized by Goodman(203). At Battle Creek, Michigan, he reported that 420 pounds per ton of ferric chloride and lime were replaced by 104 pounds per ton of combined ferric chloride and cationic polymer. The substitution resulted in higher cake moistures, but less incinerator ash.

At Baltimore, Md., Keefer evaluated the use of aluminum chlorohydrate as a sludge conditioning agent and found that it produced higher yields than ferric chloride, but also higher cake moistures(189). This material has been commonly used in England and Western Europe.

Keefer's interest was academic because aluminum chlorohydrate was not manufactured in the U.S.A. At Buffalo, New York, the use of aluminum chloride, when substituted for ferric chloride, decreased the chemical costs by 53.1 percent(190). Buffalo also used a lime slurry generated from the manufacture of acetylene; the waste carbide lime allowed significant cost reductions at many wastewater treatment plants.

Carpenter and Caron conducted numerous laboratory tests on the dewatering of board-mill and deinking paper sludges by vacuum filtration(68). Their evaluation of fiber addition and polymer treatment of the sludges produced the following findings:

1. Drainage time was significantly reduced by the addition of fiber (35 to 70% with a 25% fiber addition).

2. Increasing the sludge fiber concentration improved filtrate clarity and cake discharge.

3. Filter loading rates of a 2 percent slurry could be doubled by a 20 percent fiber addition, but 4 to 6 percent slurries were unaffected by fiber additions up to 40 percent. It was concluded that a 15 percent fiber content allowed successful vacuum filtration of most board-mill and deinking sludges.

4. Polyelectrolytes increased the dewatering rate of board-mill sludge by 184 percent at a dosage of 10 pounds per ton. The increase for deinking sludge was the same (184%) at a dosage of 5 pounds per ton.

5. Polyelectrolytes were concluded to be competitive in performance with inorganic flocculents and involved less handling and maintenance.

Carpenter and co-workers also evaluated fly ash as a vacuum filter precoat for dewatering board-mill and deinking sludges(196). These sludges represented the two extremes in paper mill sludges; because the board-mill sample was high in organic solids and the deinking sample was high in inorganic material. Conclusions from the study were:

1. Sludges not "dewaterable" by conventional vacuum filtration could be handled by fly ash precoat techniques.

2. By using a fly ash precoat, drainage rates increased when dewatering low inorganic-content sludges, but the rates decreased when dewatering highly inorganic sludges.

3. The portion of ash passing a 20 mesh screen, but retained on an 80 mesh, appeared to be the most effective ash particle size.

4. Fly ash precoating allowed a good separation of sticky cakes from filter media surfaces. Minor media blinding was noticed.

5. The ash requirement for precoating was usually less than the quantity available at board-mills burning pulverized fuel.

Sludge ash can be used instead of chemicals to improve filtration of raw sludge(179). The ash is added to the raw sludge in amounts equal to or greater than the dry solids content of the sludge. Reported advantages were: less solids in the filtrate and lower cake moisture(as little as 30 percent). Of course, adding that much dry ash decreases the sludge moisture.

Loading a rotary, vacuum filter with chemically conditioned digested primary sludge at the top rather than at the bottom was investigated at the Midland, Michigan, sewage treatment plant(254). This procedure takes advantage of gravity and the rapid drainage characteristics of polymer treated sludge. After a 15-second drying time, a filter yield of 44 pounds per square foot per hour and a cake moisture of 70 to 75 percent was obtained. Filtrate solids were 100 to 500 ppm. Loading involved the spreading of a 2.5 inch sludge-layer across the top of a rotary filter covered with an "open" saran cloth. The filter bridges were readjusted to allow maximum dewatering during the brief cycle.

Economics - The capital and operating costs of vacuum filtration vary widely, making it difficult to generalize about the process economy. Filters themselves, including necessary auxiliaries, cost \$95 to \$275 per square foot, depending on the size of the installation and the filter media (stainless steel media represents a very high cost). The cost of a building to house the equipment doubles the capital outlay(53).

Operating costs of vacuum filtration are usually greater than the capital costs. These costs normally include labor, power, chemicals and maintenance, but they should also include a portion of the administrative overhead and the cost of hauling filter cake to landfill sites, etc. MacLaren estimated that operating costs were \$10 to \$16 per ton of cake, depending on the size of the facility and the amount of chemicals used(53). His figures are low for many U.S. installations.

Simpson and Sutton surveyed costs from numerous sewage treatment plants and concluded that total operating costs varied from \$5.34 per ton to \$30.17 per ton(65c). They gave the following breakdown of the direct operating cost:

| | |
|---|---|
| Labor and direct supervision | 39% |
| Chemicals and supplies | 37% |
| Electric power | 8% |
| Maintenance | 16% |
| | 100% |

The direct costs represent 74 percent of the total operating cost figures (\$5.34 to \$30.17/ton). As expected, digested and activated sludges were more costly to dewater than raw and primary sludges. Hauling the filter cake from the plant site (costing at least 10 cents per ton-mile) could significantly increase the operating cost figure.

In 1958, Dietz reported on a survey of vacuum filtration costs at sewage treatment plants(46). The following capital costs, based on 25 years' depreciation and a 5% interest rate, were listed for different sizes of installations, determined by population served:

| | No. of People Served | | | | |
|---|---|---|---|---|---|
| | 6,500 | 10,000 | 20,000 | 30,000 | 40,000 |
| 1958 costs | $38,811 | $38,811 | $52,209 | $78,239 | $106,233 |
| 1966 costs (Est.) | $48,500 | $48,500 | $65,250 | $97,800 | $133,000 |

The above costs for vacuum filtration were in all cases lower than costs for digesters with sand beds or lagoons.

Annual capital costs were also reported by Dietz:

| | No. of People Served | | | | |
|---|---|---|---|---|---|
| | 6,500 | 10,000 | 20,000 | 30,000 | 40,000 |
| 1958 costs | $7,670 | $ 8,344 | $11,527 | $14,908 | $19,750 |
| 1966 costs (Est.) | $9,600 | $10,400 | $14,400 | $18,650 | $24,700 |

For cities of the size listed, the annual cost of vacuum filtration was always more expensive than digestion plus lagooning, but it was cheaper than digestion plus sand beds for populations over 25,000 people.

Operating costs per ton were $8.20 to $32.40 per ton with a median of about $20 per ton. The costs included chemicals, power, and labor.

Actual operating records from nearly 60 sewage treatment plants showed the following chemical costs, classified by type of sludge and plant size(253). Small plants usually had higher chemical costs because they often purchased anhydrous ferric chloride and, of course, the volume of chemicals used is relatively small (hence, higher prices). A total operating cost figure is given in parentheses, assuming chemical costs equal 40 percent of the total operating figure.

| Sludge Type | Small Plants ($/ton) | | Large Plants ($/ton) | |
|---|---|---|---|---|
| Raw primary | $ 7.00 | ($17.50) | $ 3.00 | ($ 7.50) |
| Digested primary | $11.50 | ($38.70) | $ 5.50 | ($13.75) |
| Elutriated digested primary | $ 4.00 | ($10.00) | $ 3.50 | ($ 8.75) |
| Raw primary + filter humus | $10.20 | ($25.50) | $ 6.50 | ($16.30) |
| Raw primary + activated | - | - | $10.50 | ($26.20) |
| Digested primary + filter humus | $21.50 | ($53.80) | $ 9.50 | ($23.80) |
| Digested primary + activated | $13.00 | ($32.50) | $12.50 | ($31.25) |
| Raw activated | - | - | $ 6.50 | ($16.30) |
| Elutriated digested primary + activated | - | - | $ 8.50 | ($21.28) |

In each category, the chemical and total operating costs vary widely depending on many variables such as the fraction and characteristics of industrial wastes in the sewage, the efficiency of the filtration system equipment, the cost accounting technique, and the skill of the filter operator. As mentioned before, the argument that digestion reduces overall chemical treatment costs is open to question after a review of the data. In all categories digestion increased chemical conditioning costs.

A review of the District of Columbia annual reports revealed that the cost of vacuum filtration increased significantly when treatment process at the large District plant was converted from a primary process to a high-rate aeration activated sludge process. The data listed in Table 14.1 include 3-year averages for both treatment classifications:

Table 14.1

| Sludge Type | $FeCl_3$ dose (%) | Filter Yield (Lbs./sq.ft./hr.) | *Annual Sludge Disposal Cost |
|---|---|---|---|
| Elutriated, digested primary | 4.72 | 5.96 | $105,333<br>($16/ton) |
| Elutriated, digested primary + activated | 7.48 | 4.82 | $340,000<br>($31/ton) |

*Includes operating costs for elutriation, vacuum filtration, and preparation for use as a soil conditioner.

In conclusion, the total annual cost of vacuum filtration is generally $8 to $50 per ton of dry solids dewatered.

Summary - Since 1960, vacuum filtration as a method of mechanically dewatering sludge has become very popular at cities serving populations of 10,000 and greater. It has also been a very popular technique for dewatering numerous industrial sludges. This popularity recognizes the following vacuum filter advantages: (1) a wide variety of sludges can be dewatered, (2) filters occupy a smaller space than sand beds or lagoons and are unaffected by climate, (3) a relatively dry filter cake that can be incinerated is produced, which eliminates the need for digesters, (4) the solids capture can be very good, and (5) plant operations are improved because filters offer some flexibility in scheduling so dewatering can be coordinated with other treatment processes.

However, vacuum filtration has significant disadvantages as indicated by many abandoned units(151). A survey of West Coast States revealed that 12 of 19 cities had abandoned or were considering abandoning vacuum filter facilities(180). Most of the cities reported high operating costs as the primary reason for their displeasure with filtration. Excessive chemical requirements are usually the basis for the high operating cost. Other factors involved in the unsatisfactory operations include: (1) frequent media blinding requiring shutdowns, washing and a resultant high labor cost; (2) odors from filtering raw sludge; (3) the need for duplicate units when filtering raw sludge; (4) the need for more highly trained, filter operators than are required with other dewatering techniques; (5) the lack of scientific control to accommodate fluctuations in sludge quantity and quality; and (6) the necessity for additional handling steps because filtration does not represent ultimate sludge disposal.

The most common problems in sludge filtration involve chemical conditioning and filter media blinding. Often these problems are associated with erratic sludge flows and sludge quality. To compensate for this situation, overdosing with chemicals is practiced, which leads to high chemical and maintenance costs. The latter occurs because of chemical deposits in the filter media and related equipment.

A survey of dissatisfied users of vacuum filters revealed one interesting fact--vacuum filters have been installed at locations where failure was predictable due to sludge characteristics not conducive to this dewatering technique. This situation usually occurs where biological sludges are digested, producing dilute sludges with a high concentration of small particles.

Because the filter operator is faced with a sludge whose basic character he cannot control plus equipment of fixed design, he usually considers chemical conditioning as a solution to dewatering problems. Chemicals can agglomerate small particles and produce a sludge of greater porosity and a filter cake that is less compressible.

Small treatment plants are increasingly adopting mechanical dewatering techniques. The improvements previously mentioned have encouraged this trend. However, vacuum filtration cannot usually compete economically with digestion plus sand beds, liquid land disposal or lagoons at plants with less than 10,000 population or 3.5 mgd total flow. At larger plants vacuum filters are encountering some competition from centrifuges because they offer simplicity and lower costs. But, vacuum filters will continue to be used because they can dewater many difficult sludges and capture a high percentage of solids.

Certain significant improvements have been made recently in the filtration process, but more are required. Such improvements are non-clog media, a wider selection of synthetic media, designs that include individual sludge contitioning tanks for each filter with short and gentle distribution of conditioned sludge, and the development of polymeric flocculents which have lower capital and operating costs.

Additional improvements are in order to replace some of the art of filtration with new technology. A basic step would be the design of equipment to deliver sludge to the filter at a uniform rate. Another would be to incorporate the equipment flexibility discussed in the design parameters. Sludge quality is difficult to predict, particularly over the life of equipment that might last as long as 25 years, so flexibility to accommodate unexpected sludge characteristics is desirable.

Instrumentation to accurately proportion conditioning chemicals to the sludge could greatly reduce operating costs. This instrumentation could measure sludge flows as well as the demand for flocculating chemicals.

Further research in sludge conditioning is warranted. This may involve heat treatment, freezing, or the use of electricity, inert additives or any number of other techniques (see Sludge Conditioning and Dewatering - Unusual Processes chapter). Garber's work on thermophilic digestion(140) with an objective of producing an easily dewatered sludge should be renewed. Economics of systems that produce a better ratio of primary to secondary sludge should be explored because increases in the proportion of primary sludge decrease dewatering costs. This can be achieved by chemical flocculation in primary sedimentation basins and perhaps by adjusting biological treatment so that it creates a minimum of solids.

Handling primary and secondary sludge separately should be investigated. Digesting primary sludge and later mixing it with raw secondary sludges may produce lower dewatering costs. New filtration equipment such as the top load filter described by Emmett and Dahlstrom(245) should be explored further.

## B. Pressure Filtration and Miscellaneous Processes

General - Mechanical pressure filtration of sewage sludge is a common practice outside the United States. In the United States pressure filtration has been used by industry in a variety of process dewatering systems but its use for dewatering waste sludges is uncommon. In recent years the use of "plug" presses for dewatering waste sludges has been promoted in this country. The design of these systems takes advantage of free water drainage followed by the application of low pressures.

Pressure Filtration - It has long been known that pressure filtration could effectively remove both the free and interstitial water from a wide variety of sludges. Pressure filtration has never been enthusiastically accepted in this country because it is a batch operation involving high labor and maintenance costs. Where pressure filtration is in use, leaf filters are the most common type of unit.

Like vacuum filtration, a porous media is used in leaf filters to separate solids from the liquid. The solids are captured in the media pores; they build up on the media surface; and they reinforce the media in its solid-liquid separation action. Sludge pumps provide the energy to force the water through the media.

Thompson and Proctor described the use of a mechanical filter press in England to produce a filter-cake with an unusually low moisture content of 40 percent, the feed solids averaged 10 percent(280). The operational procedure described is typical: (1) lime is added for sludge conditioning (20 lbs. per dry ton), (2) the lime treated sludge is stored 48 hours, (3) the filter is filled and the sludge pressed in 3 hours, and (4) the filter is unloaded in one hour and the equipment cleaned. Two pressings per day shift per unit are possible with the above schedule. During warmer weather the sludge is also treated with 6 ppm chlorine to prevent odors and filter cloth blinding.

In Hamilton, Scotland, presses were successfully used for dewatering sewage sludges(67). Elutriated digested sludge was conditioned with 120 pounds per ton aluminum chloride and pumped to presses at pressures up to 90 psi. The 4 percent feed sludge required a filtration time of 5-1/2 to 18 hours to produce a sludge cake 1-1/4 inches thick.

Lime, aluminum chloride, aluminum chlorohydrate, and ferric salts have been commonly used overseas to condition sludge prior to pressing. The successful use of ash precoating has also been reported. Minimum chemical costs are supposed to be the major advantage of press filters over vacuum filters.

Leaf filters represent an attempt to dewater sludge in a small space quickly. But when compared to other dewatering methods, they have major disadvantages: (1) batch operation, (2) high operation and maintenance costs, and (3) high filter-cake moisture. The above disadvantages together with the high labor costs in the United States preclude the use of leaf filters in most situations. These disadvantages were apparent in a recent evaluation of pressure and vacuum filters for dewatering board-mill and deinking sludges. The conclusion reached after comparative tests was that vacuum filters are superior(249).

Caron and Carpenter reported on the use of other mechanical presses, screw and hydraulic, to dewater papermill sludges(68). The hydraulic press dewatered board-mill sludge to 40 percent solids at a pressure of 300 psi and a pressing time of five minutes. It appears that little additional dewatering was gained by increasing the pressures above 300 psi.

Hydraulic and screw presses, while effectively dewatering sludges, have the major disadvantage of requiring a thickened sludge feed.

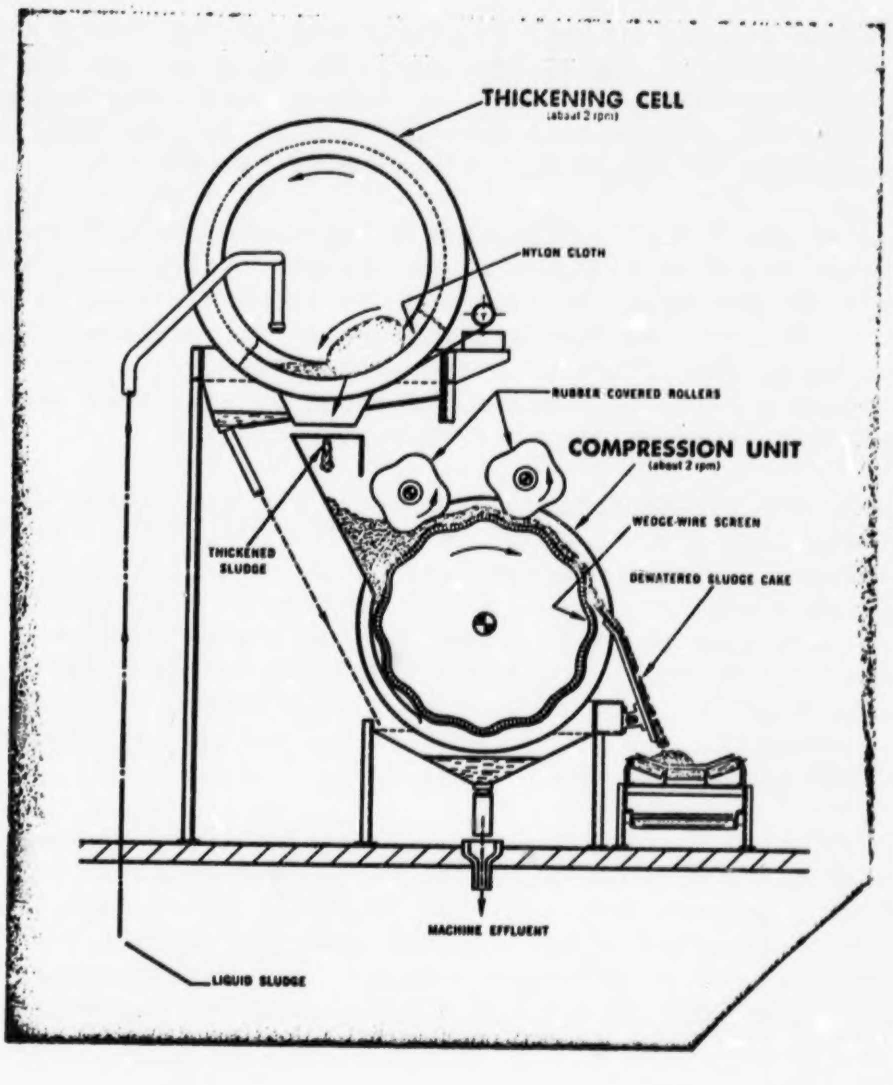
Their use may therefore be limited to situations similar to those reported by Coogan and Stovall(325). They described the use of a circular V-press to dewater papermill sludge already partially dewatered by a centrifuge. Further dewatering was recommended because ultimate disposal was by incineration, and papermill sludges are difficult to incinerate without the use of auxiliary fuel. Feed solids to the press averaged 20 to 25 percent solids and the press delivered sludge to the incinerator averaging 33 to 38 percent solids. In the future, more industrial sludges will be incinerated as space for lagoons disappears. Then, pressing as described above, may become more popular.

Free Drainage and "Plug" Presses - In recent years a few small communities and some industries have installed dewatering equipment that takes advantage of free water drainage followed by the application of low pressures. The two proprietary systems using this technique are the "Roto-Plug"(283) and "DCG Solids Concentrator."(278) One objective of both systems is to avoid a critical pressure whereby the sludge solids structure breaks down blinding the filter media. Another objective is to avoid large dosages of flocculents necessary to build a firm solids structure. Most sewage sludges consist of gelatinous particles that collapse under low mechanical pressures. The use of chemicals or fibrous materials to condition sludges increases the allowable critical pressure, but the "plug" presses were developed to minimize the need for these materials.

Dewatering in the two proprietary systems is accomplished in successive stages with increasing pressure in each stage. This delays the period of heavier pressures until the sludge concentration has increased to a point where pressure can be applied without collapsing the solids structure(278). The manufacturers of the proprietary equipment have claimed that sludge conditioning materials are unnecessary with fresh sludges because a natural floc already exists, but polymers or waste paper pulp are useful for conditioning septic or digested sludges to prevent structural collapse of the solids(283).

The "plug" processes begin with a thickening step using free drainage of easily separated water through a nylon cloth under a low pressure of 1 to 1.5 inches of water. As solids accumulate, a rolling mass of sludge or plug is formed which further squeezes water from the sludge due to it own weight. Figure 14.XI depicts this and following steps. The plug forces the thickened sludge into the cake formation or compression unit. Here the sludge is

Figure 14.XI


THICKENING CELL
(about 2 rpm)
NYLON CLOTH
RUBBER COVERED ROLLERS
COMPRESSION UNIT
(about 2 rpm)
WEDGE-WIRE SCREEN
THICKENED SLUDGE
DEWATERED SLUDGE CAKE
MACHINE EFFLUENT
LIQUID SLUDGE

*Roto-Plug Flow Diagram.*

(Reprinted by permission Nichols Engineering & Research Corp.)

pressed at about 10 to 15 psi between a wedge-wire drum and rubber covered rollers. Additional compression filters can be installed in series if further dewatering is required. Pressed sludge is incinerated or hauled away to land disposal.

Advantages claimed by both manufacturers of the "plug" process are: (1) little if any sludge conditioning materials are necessary, (2) power consumption is low, (3) only a small area is required for equipment, (4) uniform cake production is possible, and (5) the equipment is simple and economical[278, 283].

Basically the "plug" manufacturers have acknowledged the difficult characteristics of sludge such as its weak solids structure. They attempt to work with the sludge as it is rather than to alter its basic character. By taking advantage of free drainage, they remove large quantities of water very economically, and by operating below a critical pressure of about 20 psi, they avoid operational problems common with vacuum filters.

How well has the equipment performed? The published data show cake moistures from 65 to 85 percent[66, 278, 282]. At Caldwell, New Jersey, cationic polymers were used to condition the digested sludge at a cost of $8 to $10 per dry ton of solids[282]. Polyelectrolytes or waste paper pulp were also used at a number of other "plug" press locations. Because of the excellent idea of using free drainage of unbound sludge water, it seems logical to encourage the use of flocculents for solids agglomeration and even more rapid drainage of free water.

A variation of the "plug" press was described by MacNeal[279]. He reported on the use of a Rice Barton Water Extractor for dewatering primary and activated sludge from a papermill. This equipment consisted of an inclined constant-pitch screw rotating at low speeds in a perforated basket. The dilute sludge was fed at the bottom and conveyed by the screw to the top where a plug was formed and later broken up prior to discharge.

Data collected from test runs showed that a 2.7 percent solids feed sludge can be dewatered to a 15 percent sludge cake. This degree of dewatering would not be adequate for many installations. Another major disadvantage was the reported low solids capture of 70 percent. If the solids capture could be improved by the use of conditioning agents, this equipment might be useful as a first step in a two-step dewatering system.

Heymann Sludge Thickening Process - More than 20 sewage treatment plants in Germany and Switzerland have used the "Heymann" process consisting of vibrating screens and rotary filter presses[132].

Digested sludge was dewatered to 35 to 40 percent solids using a combination of a coarse screen, a sonic screen, a sonic filter, and a roll press(66). The screening of sludge by vibrating screens is discussed in the Screening section of this chapter.

Data from Germany, where the Heymann process was developed in 1954, disclosed that the average raw sludge moisture was reduced from a feed of 93.4 percent to a roller press cake of 74.5 percent. Swiss data showed that the moisture was reduced from roller pressing alone of 80.6 percent in the roller feed to 75.8 percent in the pressed cake(132).

The advantages claimed for the Heymann process are that no chemical conditioning of sludge is required and the dewatered sludge has good drying characteristics. However, two major disadvantages preclude its use in most installations. First, the filtrate solids were reported as an excessive 2.16 to 9.2 percent in U.S.A. tests and, second, the roller pressed cake had a high moisture content (65 to 74.3%)(132).

Two other sewage sludge press-dewatering processes have been described in the literature. One involved sludge thickening followed by mixing with previously dried sludge; moisture concentrations of 50 to 55 percent were obtained. This mixture was then extruded into hollow shapes similar to building tile. The extruded shapes were air or heat-dried, used for fertilizer, or incinerated(284). The other process started with a 5 percent sludge which passes through sieves and roller mills. A 20 percent reduction in the sludge water content was reported(285).

Summary - Dewatering waste sludges by pressing has not been widely adopted for two major reasons: (1) the resultant cake is not sufficiently dried, and (2) the separated water contains excessive solids. Improvements in equipment and/or the use of chemicals or other sludge conditioning materials could at least partially solve these limitations. The limitations are important because recycling effluent solids decreases overall treatment plant efficiencies, and the high cake moisture limits the ultimate sludge disposal choices or makes them unnecessarily expensive. Pressing techniques may be limited to a two-stage dewatering system installed prior to incineration or heat drying.

## C. Centrifugation

General - Numerous consulting engineers and equipment manufacturers have believed that the centrifuge will replace the vacuum filter as the most popular mechanical device for dewatering sludge. The centrifuge is not new to waste treatment; a perforated basket type was used in Germany to dewater raw primary sludge as long ago as 1902. In Milwaukee, a centrifuge was evaluated in 1920, but the operating results on sewage sludge dewatering were disappointing(126). However, centrifuges are becoming increasingly popular today due to design improvement, greater sales promotion by manufacturers, and increased dissemination of successful performance data.

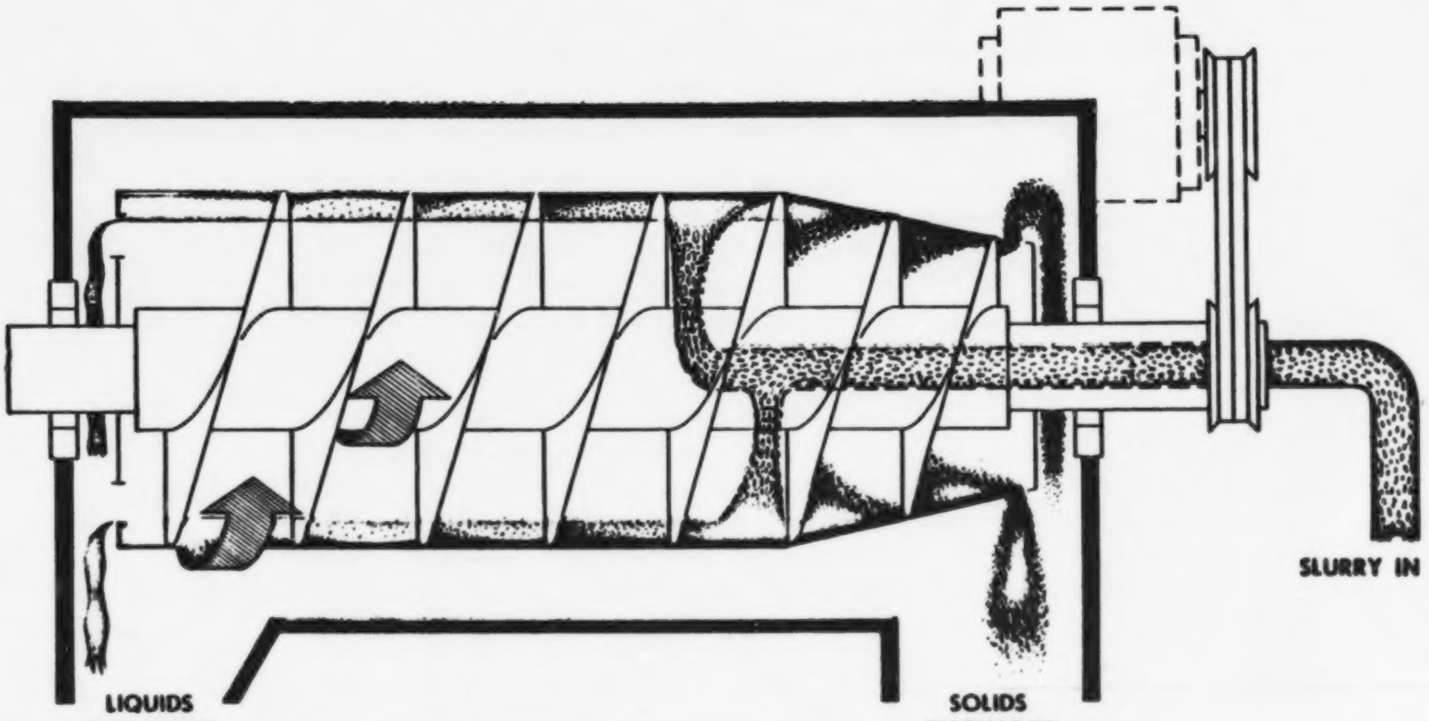
Centrifugation has some inherent advantages over vacuum filtration and other processes used to dewater sludge. It is simple, compact, totally enclosed, flexible, normally used without chemical aids, and the costs are moderate. These advantages have resulted in the installation of 50 units around the country for dewatering sludges(262). Industry particularly has accepted centrifuges in part due to their low capital cost, simplicity of operation, and effectiveness with difficult-to-dewater sludges.

Theory and Operation - The most effective centrifuges to dewater waste sludges are horizontal, cylindrical-conical, solid bowl machines. Basket centrifuges dewater sludges effectively but liquid clarification is poor. Disc-type machines do a good job of clarification but their dewatering capabilities leave much to be desired(126).

Basically, centrifuges separate solids from the liquid through sedimentation and centrifugal force. In a typical unit, (Figure 14.XII) sludge is fed through a stationary feed tube along the centerline of the bowl through the hub of the screw conveyor. The screw conveyor is mounted inside the rotating conical bowl. It rotates at a slightly lower speed than the bowl. Sludge leaves the end of the feed tube, is accelerated, passes through the ports in the conveyor shaft, and is distributed to the periphery of the bowl. Solids settle through the liquid pool, are compacted by centrifugal force against the walls of the bowl, and are conveyed by the screw conveyor to the drying or beach area of the bowl. The beach area is an inclined section of the bowl where further dewatering occurs before the solids are discharged. Separated liquid is discharged continuously over adjustable weirs at the opposite end of the bowl.

Parameters - In centrifugation, process variables are: (1) feed rate, (2) sludge solids characteristics, (3) feed consistency, (4) temperature, and (5) chemical additives. Machine variables are: (1) bowl design, (2) bowl speed, (3) pool volume, and (4) conveyor speed(126).

Figure 14.XII


SLURRY IN
LIQUIDS DISCHARGE
SOLIDS DISCHARGE

Operation of horizontal Super-D-Canter centrifuges

(Reprinted by permission Sharples-Equipment Division Pennsalt Chemical Corporation)

Two factors usually determine the success or failure of centrifugation--cake dryness and solids recovery. Guidi summarized the effect of the various parameters on these two factors(126):

| To Increase Cake Dryness | To Increase Solids Recovery |
|---|---|
| 1. Increase bowl speed | 1. Increase bowl speed |
| 2. Decrease pool volume | 2. Increase pool volume |
| 3. Decrease conveyor speed | 3. Decrease conveyor speed |
| 4. Increase feed rate | 4. Decrease feed rate |
| 5. Decrease feed consistency | 5. Increase temperature |
| 6. Increase temperature | 6. Use flocculents |
| 7. Do not use flocculents | 7. Increase feed consistency |

The effect of bowl speed on solids recovery or capture is shown in Figure 14.XIII for a mixture of raw primary and activated sewage sludge(126). Blosser described very similar data for papermill sludges(260). While the ideal speed for each application is determined by many factors, the data showed improved captures at higher speeds.

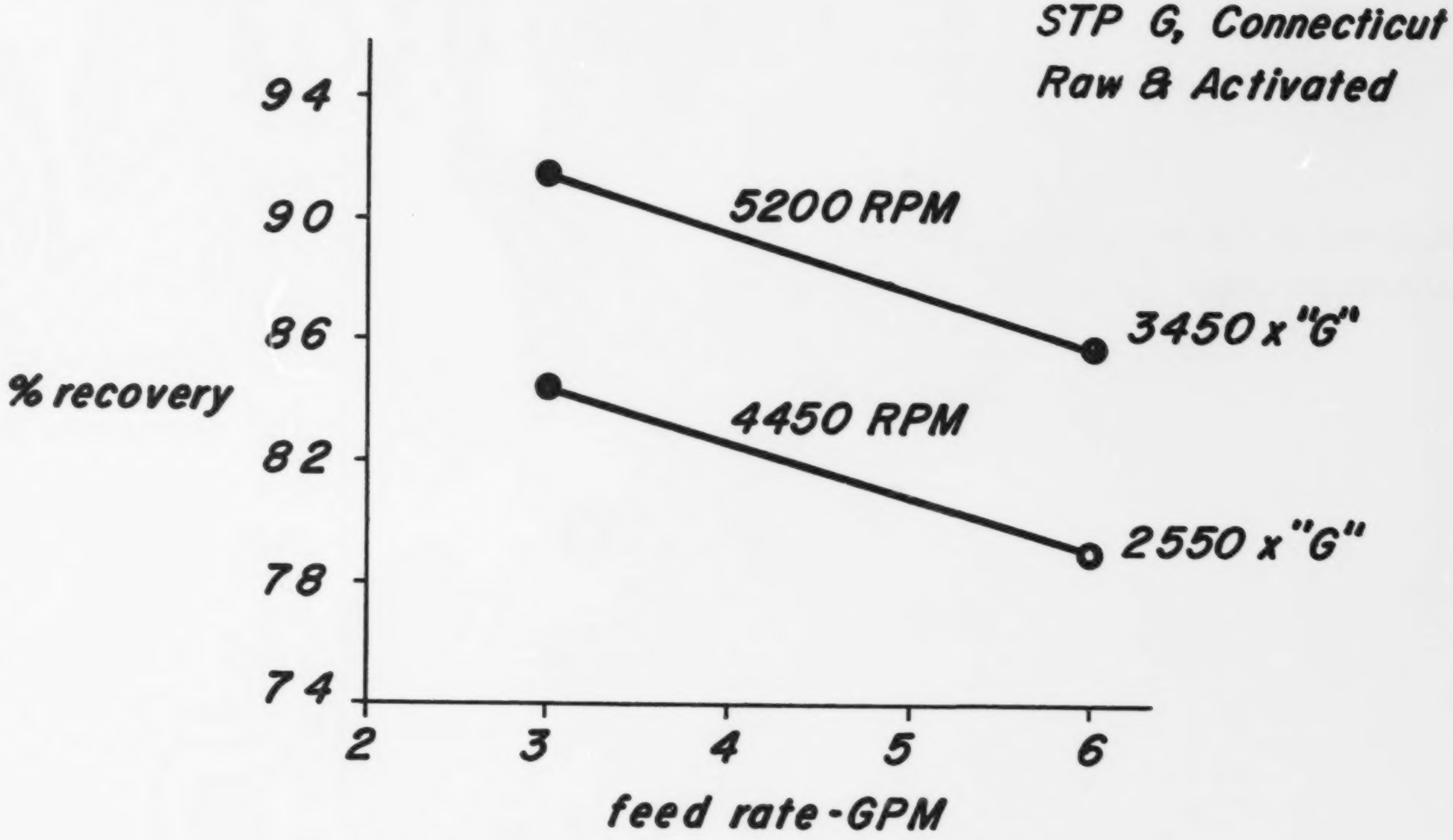
Blosser and Guidi agreed that an increase in the pool volume, or detention time, increased the solids recovery, as shown in Figure 14.XIV(126). This increased recovery, however, is achieved at the sacrifice of cake dryness, as described in Figure 14.XV(126). The incompatibility of cake dryness and solids recovery is also shown--in Figure 14.XVI--for digested primary and activated sewage sludge(126).

Papermill sludge and digested primary sewage sludge also responded similarly to changes in the feed rate(126, 260). Figure 14.XVII by Guidi shows a decreasing solids recovery with increasing feed rates(126). The effect of bowl speed on cake dryness is described by Figure 14.XVIII(126). Increases in bowl speed increased the centrifuge cake-solids content.

Figure 14.XIX shows the effect of chemical additives on the centrifuge dewatering process(193). The graph was developed from data generated from the dewatering of a chemical plant sludge consisting of both raw primary and activated sludge. Low dosages of organic polyelectrolytes greatly increased solids

Figure 14.XIII

EFFECT of BOWL SPEED on RECOVERY

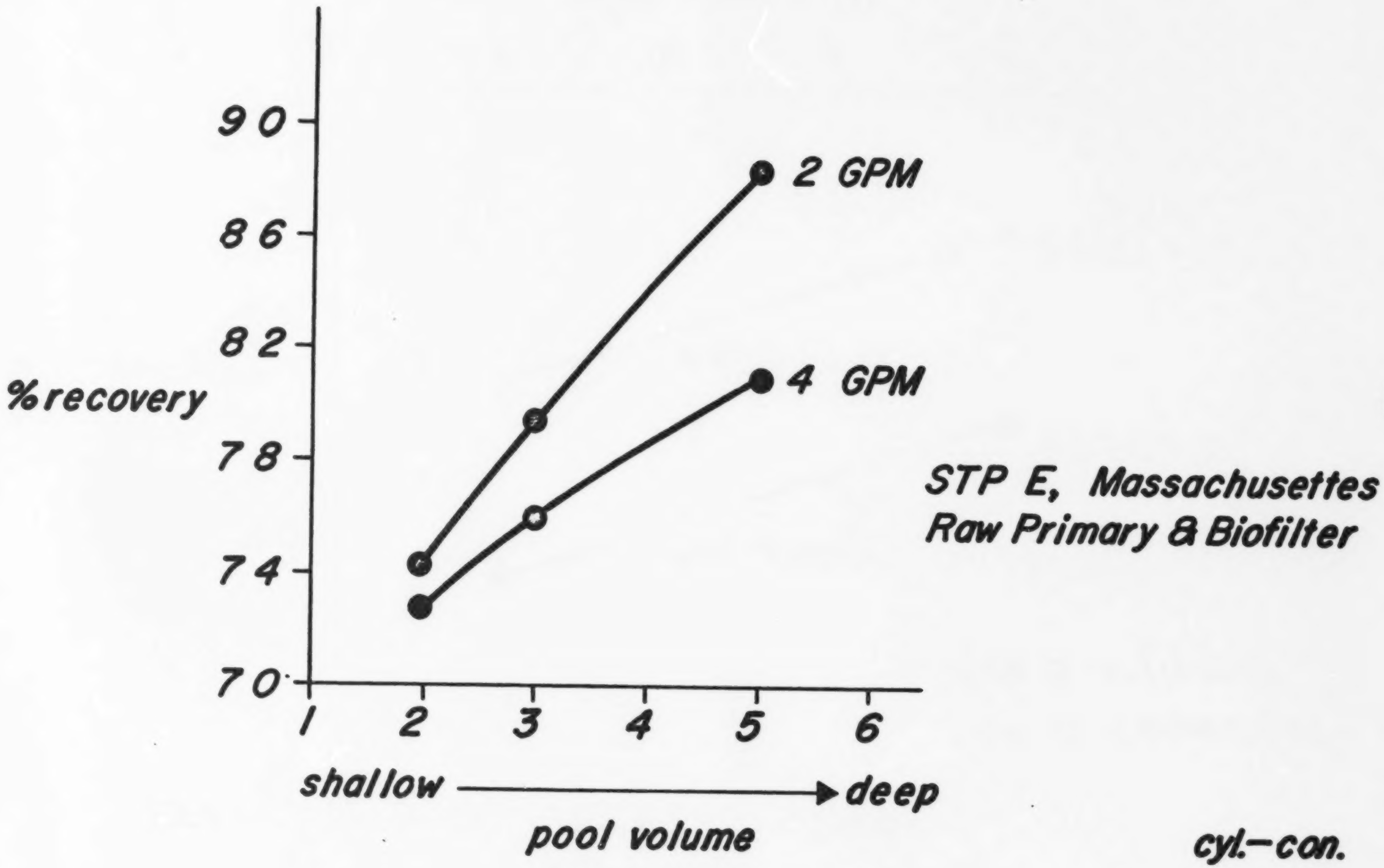


(Courtesy Dorr-Oliver, Inc.)

cyl.-con.

Figure 14.XIV

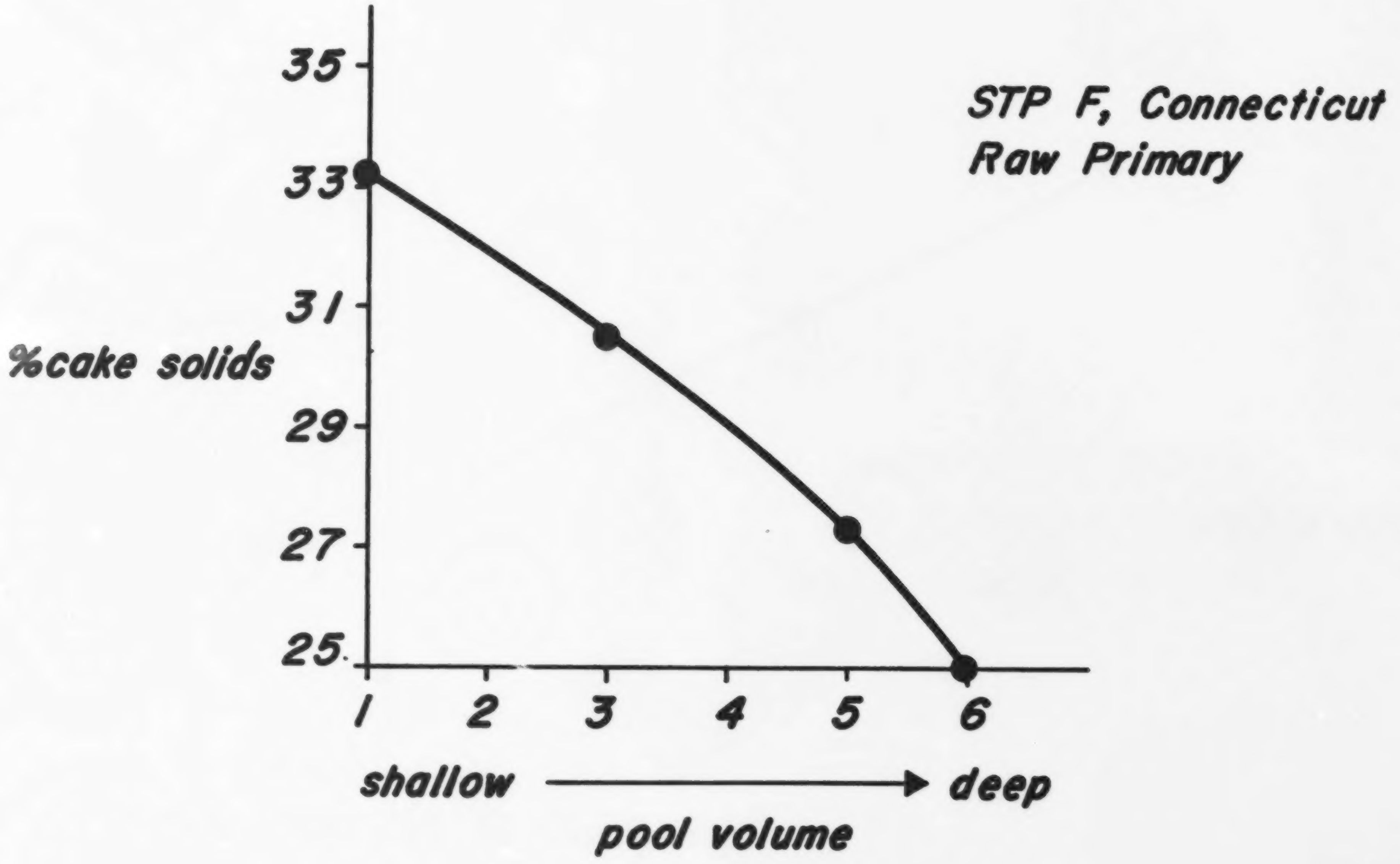
RECOVERY Vs POOL VOLUME



(Courtesy Dorr-Oliver, Inc.)

Figure 14.XV

CAKE DRYNESS Vs POOL VOLUME

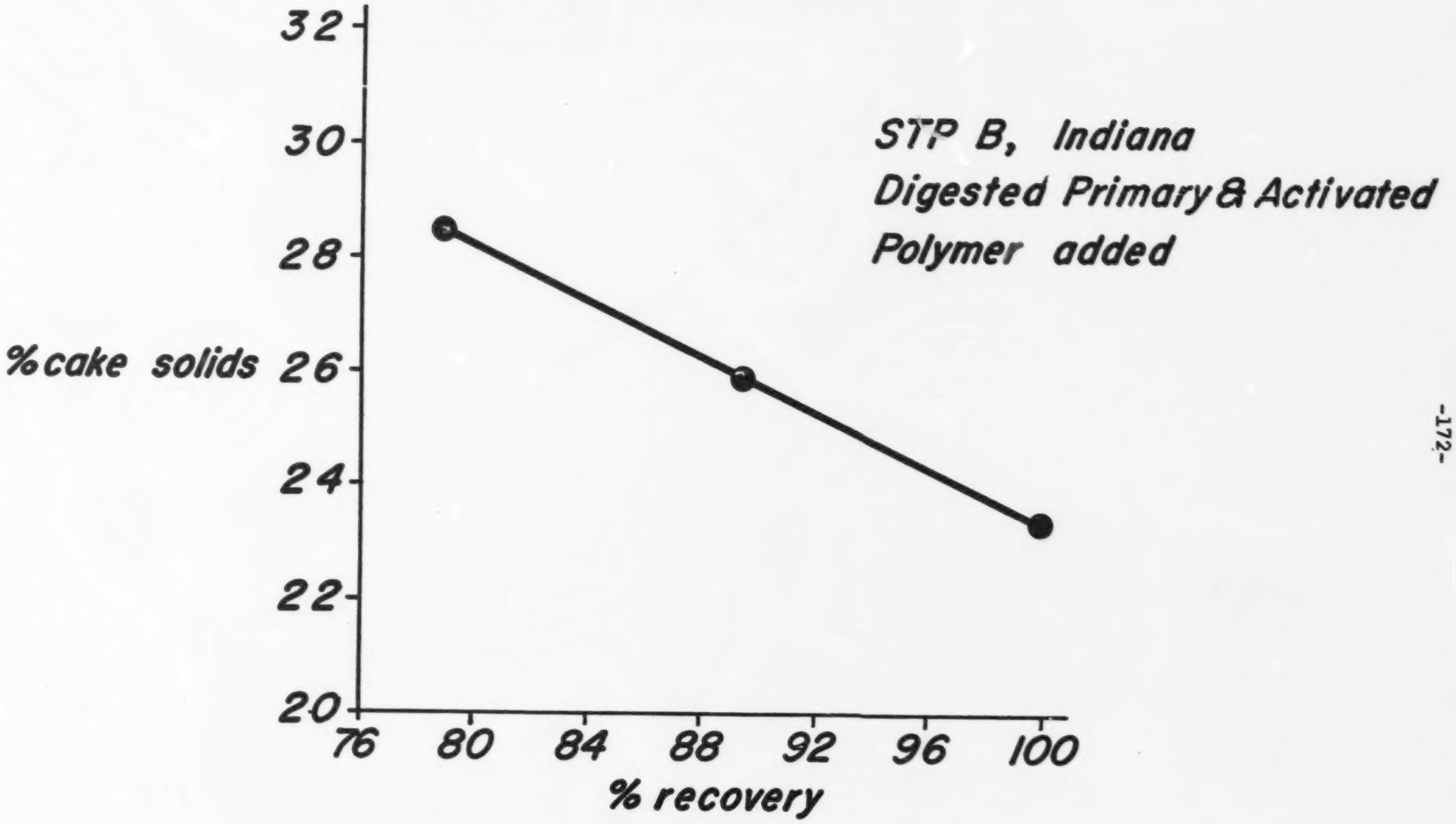


(Courtesy Dorr-Oliver, Inc.)

con.

Figure 14.XVI

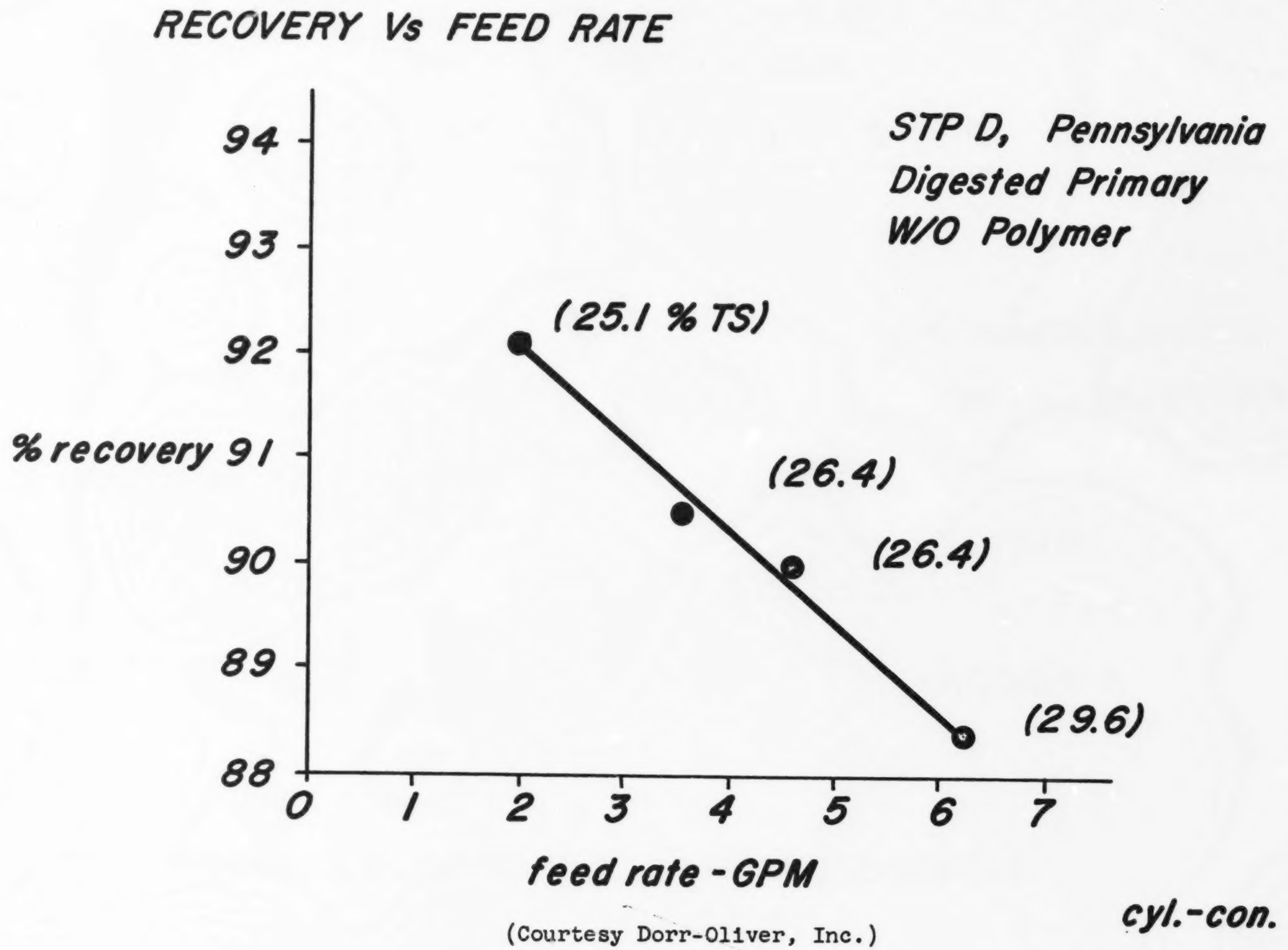
CAKE DRYNESS Vs RECOVERY



(Courtesy Dorr-Oliver, Inc.)

cyl.-con.

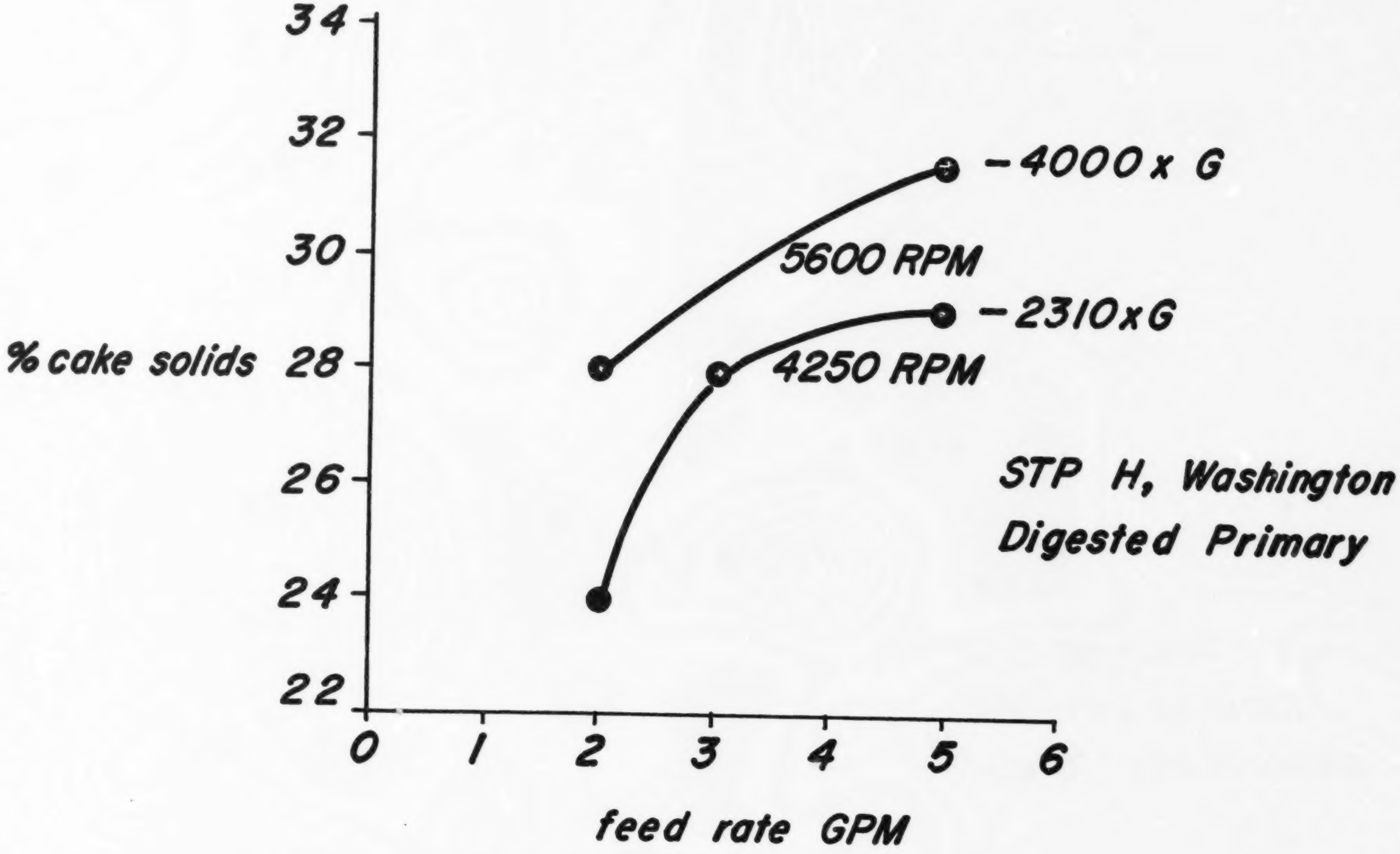
Figure 14.XVII



(Courtesy Dorr-Oliver, Inc.)

Figure 14.XVIII

EFFECT of BOWL SPEED on CAKE DRYNESS



(Courtesy Dorr-Oliver, Inc.)

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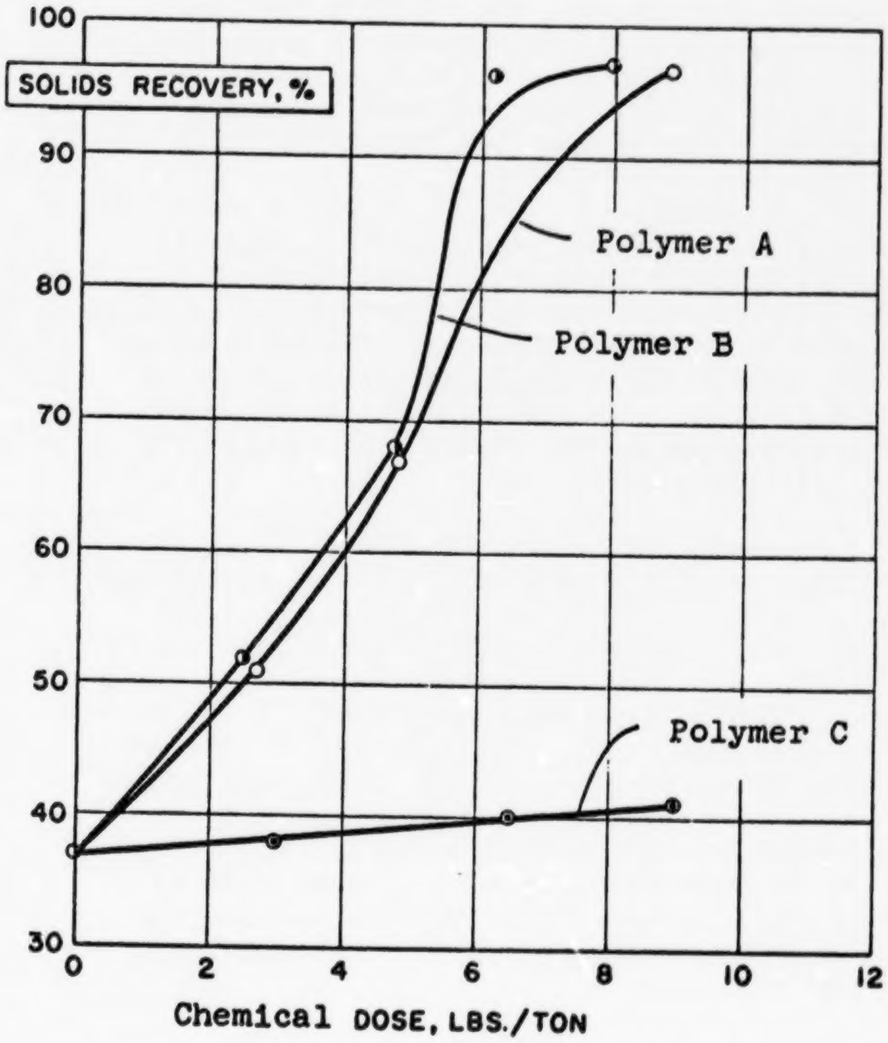
Figure 14.XIX



*Centrifugation of primary-activated sludge mixture.*

(Reprinted by permission Schools of Engineering Purdue University recovery. Chemical treatment, however, usually lowers the cake dryness (probably due to the capture of the fine solids) so a compromise on objectives is necessary (dryness vs. recovery). Amero stated that polymers permit higher unit loadings as well as higher solids recovery. He believed 90 percent recovery is possible with chemical treatment(262).

Obviously from the graphs, many parameters affect the ultimate centrifuge performance. Fortunately, the machines made today are designed with some flexibility, so adjustments can be made for varying conditions. The many parameters and how they are inter-related must be evaluated in each case to attain operating procedures that will deliver the "best" dewatered cake.

Performance - For many years the Los Angeles County Sanitary Districts have been using centrifuges to dewater digested primary sludge(18, 258). Sludge with an average solids content of 5 percent is dewatered to 30 or 35 percent. Solids capture up to 66 percent is possible when centrifuges are operated at speeds of 1,020 to 1,580 rpm. Centrate is screened to remove floatables and then discharged to the ocean. Centrifuge cake is sold as a fertilizer ingredient.

A number of other California cities have used centrifuges to dewater sewage sludges. A sludge cake of 30 percent is obtained from a digested sludge feed of 4.5 to 5 percent at the North San Mateo County Sanitary District plant(255, 256). The centrifuge is operated 9 hours per week; the cake produced is used to fertilize city parks. Solids capture is very poor, as indicated by a centrate containing from 2 to 2.5 percent solids. Existing centrate drying beds are not used however for additional solids removal because the centrate solids resettle upon recycle to the head of the treatment plant. At San Leandro, California, a cake of 26 percent is generated from a 3.5 percent feed of raw sewage and industrial sludges. The centrate contains 1.9 percent solids; it causes some deterioration in overall treatment plant efficiency upon recycle(256).

Caron, Blosser and Jenkins reported data from centrifuge dewatering of many paper sludges(263, 264). Typical results are:

| Mill and Sludge Type | Feed Solids (%) | Cake Solids (%) | Solids Capture (%) |
|---|---|---|---|
| 1. Save-all sludge from felt manufacture | 6 | 35 to 40 | 90 |
| 2. Fine paper | 3 to 5 | 22 to 30 | 88 to 95 |
| 3. Save-all sludge from speciality mill | 1 to 5 | 22 to 40 | 75 to 98 |
| 4. Boardmill | 2 to 5 | 22 to 30 | 85 to 95 |
| 5. Deinking | 5 to 7 | 25 to 30 | 85 to 90 |
| 6. Tissue | 2 to 3 | 20 to 35 | 85 to 92 |
| 7. Kraft mill | 1 to 5 | 22 to 34 | 82 to 95 |

According to Jenkins dewatering allows ultimate solids disposal by landfilling, incineration, or by-product use in rough paper or low price fiber boards(263). He stated that the use of flocculents increase centrifuge capacity and dewatering efficiency.

The use of polymeric flocculents in a centrifuge to dewater primary and waste-activated sludge, generated from chemical process, improved efficiencies as follows(225):

|  | Control (No Flocculents) | (With Flocculents) |
|---|---|---|
| Cake production | 25,000 lbs/day | 50,000 lbs/day |
| Solids capture | 30 to 45 percent | 95 percent |
| Centrate solids | 27,000 ppm | 300 ppm |

Efficiency improvements of a similar magnitude were reported for the dewatering of digested primary and secondary sewage sludge(200):

| | Control (Without Cationic Polymer) | Treatment With 10 Lbs./Ton Flocculent |
|---|---|---|
| Feed solids | 7.2% | 7.5% |
| Bowl speed | 1500 rpm | 1500 rpm |
| Centrate solids | 40,500 ppm | 1700 ppm |
| Cake solids | 18.2% | 15.7% |
| Removal efficiency | 43.8% | 97.8% |

Centrifuges have demonstrated their usefulness in by-product recovery at meat packing plants. Dewatering floated and screened fats to 35 percent solids has been possible in a centrifuge(429). Because the feed solids vary from 0 to 15 percent, the flexibility offered by centrifuges is important.

Guidi summarized the performance of conical and cylindrical-conical centrifuges in dewatering many different types of pulp and paper mill sludges (see Figure 14.XX) as well as sewage sludges (see Figure 14.XXI). He found that: (1) primary sewage sludge can be dewatered to 28 to 35 percent, (2) biofilter 20 to 26 percent, and (3) activated 18 to 24 percent(126).

Economics - Centrifuge dewatering costs vary with the sludge to be treated, the daily volume and consistency of the sludge, and whether fine centrate solids must be captured in the machine. Caron and Blosser estimated that centrifuge operation and maintenance costs for the paper industry were $4 to $20 per ton of dry solids excluding cake hauling(264). They listed f.o.b. capital costs as follows (assume 1 gpm per rated HP):

| 25 HP | 40 HP | 100 HP | 250 HP |
|---|---|---|---|
| $20,000 | $28,000 | $40,000 | $50,000 |

Installation and auxiliary equipment, not including housing, adds $12,000 to $25,000 to the cost. The machine-cost figures compare favorably with those from San Leandro, Calif., ($30,000 for 75 HP) and N. San Mateo ($11,000 for 15 HP)(256).

The centrifuge dewatering costs at the Los Angeles County Sanitary District have been reported to be about $4.25 per ton of dry solids recovered(258). If 60 percent solids recovery is assumed, the cost per ton of solids feed is $7.10 per ton. This figure includes capital, power, labor and maintenance. Whey polymeric flocculents are required, the operating costs of centrifuges could double as indicated by the data shown in Figure 14.XXII(126). Chemical costs for various sludges are $6 to $20 per ton.

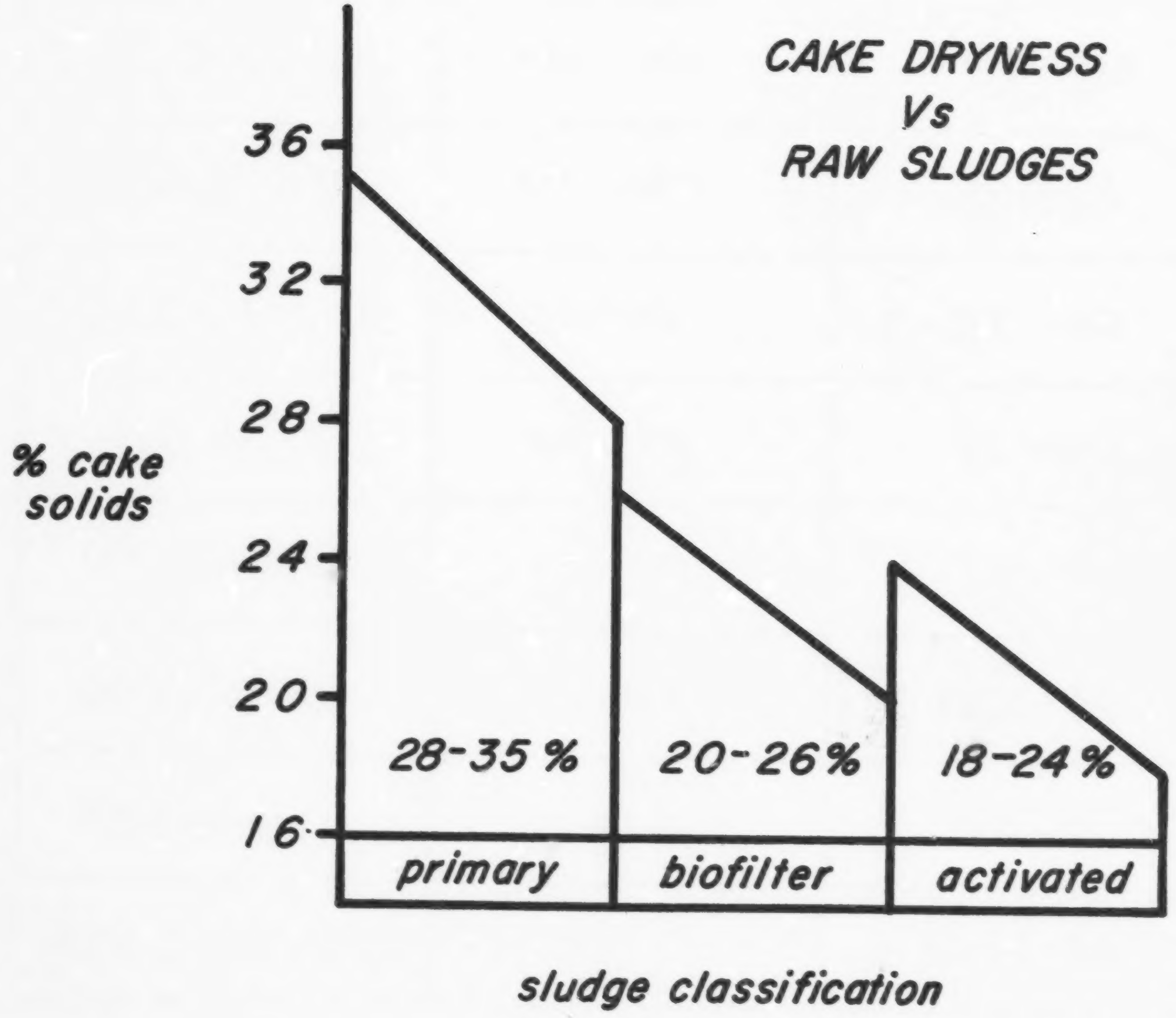
Figure 14.XX

## PULP & PAPER WASTE

| WASTE SLUDGE | UNIT | % CAKE SOLIDS | % RECOVERY |
|---|---|---|---|
| BOXBOARD | conical | 28-36 | 86-94 |
| BOXBOARD | conical | 22-28 | 88-93 |
| HARDBOARD | conical | 26-28 | 85-95 |
| WHITE WATER | conical | 21-30 | 78-94 |
| BARKER WASTE | conical | 32-40 | 90-93 |
| KRAFT MILL | cyl.-con. | 36-43 | 78-89 |
| LIME & PAPER | cyl.-con. | 45-50 | 90 |
| PULP WASTE | cyl.-con | 15 | 90 |

(Courtesy Dorr-Oliver, Inc.)

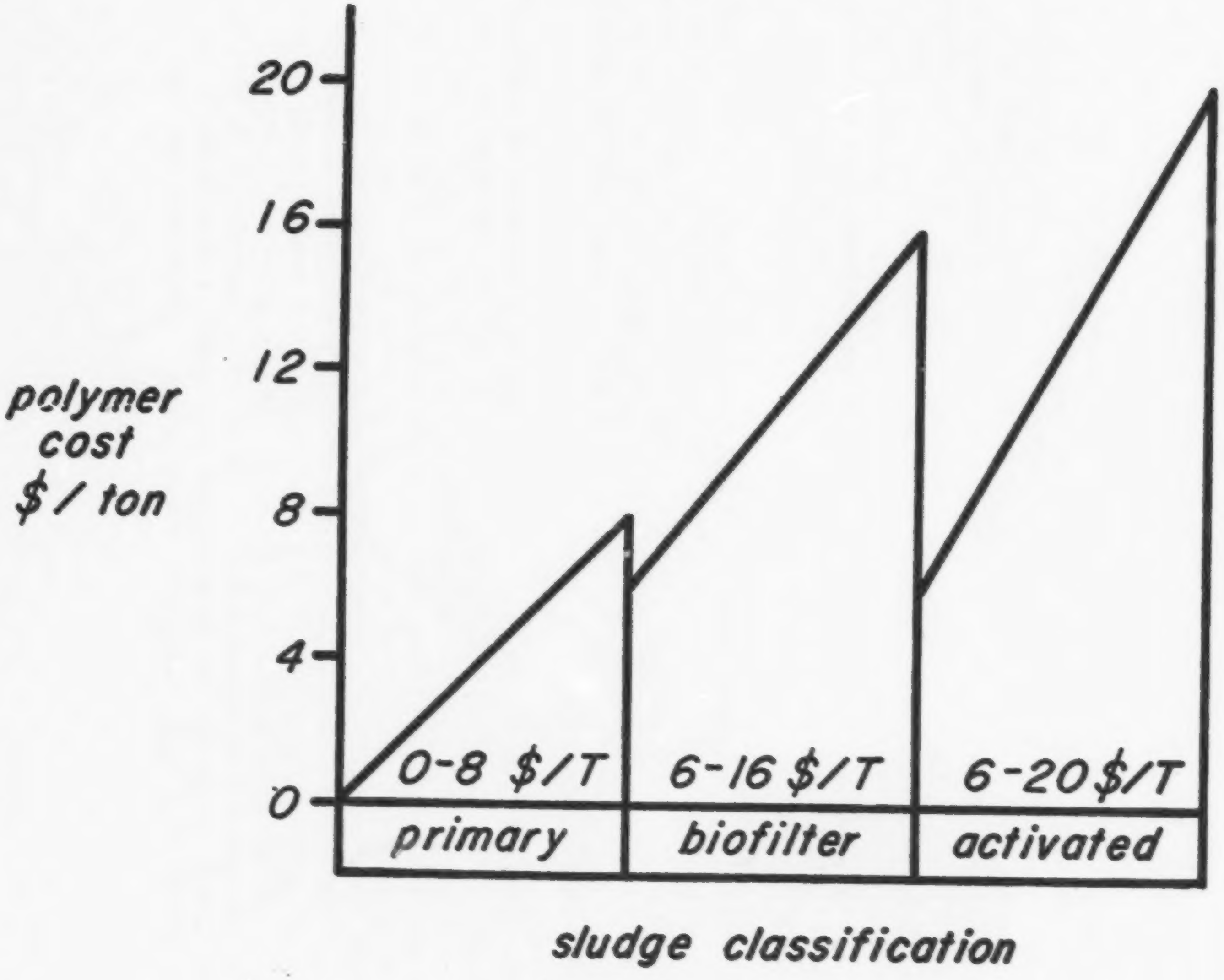
Figure 14.XXI



(Courtesy Dorr-Oliver, Inc.)

Figure 14.XXII

POLYMER REQUIREMENTS



(Courtesy Dorr-Oliver, Inc.)

In general, for any specific dewatering application, centrifuge capital costs are about 30 percent less than the capital cost of vacuum filters. The operating costs of the two pieces of mechanical equipment are nearly equal. Vacuum filtration almost always requires chemical conditioning of the sludge, which can cost a substantial sum. Chemicals have not been used in most centrifuge operations. Maintenance is more costly with centrifuges than with vacuum filters because certain parts regularly wear out. Overall, the dewatering costs for centrifugation appear to be less than vacuum filtration except perhaps when biological sewage sludges or difficult industrial sludges are dewatered. The range of total annual costs is \$5 to \$35 per ton. A typical average is \$12 per ton.

Summary - Centrifuges are being installed in more and more wastewater treatment plants for the following reasons: (1) the capital cost is low in comparison with other mechanical equipment, (2) the operating and maintenance costs are moderate, (3) the unit is totally enclosed so odors are minimized, (4) the unit is simple and will fit in a small space, (5) chemical conditioning of the sludge is often not required, (6) the unit is flexible in that it can handle a wide variety of solids and function as a thickening as well as a dewatering device, (7) little supervision is required, and (8) the centrifuge can dewater some industrial sludges that cannot be handled by vacuum filters.

The disadvantages associated with centrifugation are: (1) without the use of chemicals the solids capture is often very poor, and chemical costs can be substantial; (2) trash must often be removed from the centrifuge feed by screening; (3) cake solids are often lower than those resulting from vacuum filtration; and (4) maintenance costs are high.

The poor quality of the centrate is a major problem with centrifuges. The fine solids in centrate recycled to the head of the treatment plant sometimes resist settling and as a result, their concentrations in the treatment system gradually build up. The centrate from raw sludge dewatering can also cause odor problems when recycled. Flocculents can be used to increase solids captures, often to any degree desired, as well as to materially increase the capacity (solids loading) of the centrifuges. However, the use of chemicals nullifies the major advandate claimed for centrifuges--moderate operating costs. New techniques should be explored to handle centrate separately without returning it to other conventional treatment plant units. These may include aeration for stabilization, mixing with incinerator ash prior to filtration, or combining with digester supernatant liquor and lime to produce a liquid fertilizer.

Centrifuges will continue to become more popular because of their many advantages. However, while they dewater fibrous and lime sludge easily, they do not completely replace vacuum filters because they do not easily dewater biological sludge and clay slurries.

Research in two areas has made centrifuges more acceptable to the waste treatment field in recent years -- improved machine design and the application of chemicals. Continued research in these areas is recommended.

## D. Sand Bed Drying

General - The most common method of dewatering sewage sludge is by drying on open or covered sand beds. U. S. Public Health Service Publication Number 609 (1958) stated that 71 percent of all municipal plants in the United States operated sludge drying beds. A survey of 24 leading consulting engineers and 30 State water pollution control agencies in many different geographic locations indicated sand bed dewatering is the most common dewatering method(59). Over 6,000 sewage treatment plants in the United States use this system of sludge drying. Sand bed drying is also the most common technique in England and Europe.

While sand beds are particularly suitable for small installations, they are used at treatment plants of all sizes and in geographical areas of widely varying climates. U.S.P.H.S. Publication 609 pointed out that cities with less than 10,000 people especially favor air drying of sludge on sand beds. Kelman and Priesing reported that 60 percent of the cities having treatment plants and a population between 25,000 and 100,000 use drying beds. Also, 38 percent of the cities with treatment plants and populations greater than 100,000 have drying beds(198).

Many industrial sludges are also dewatered on drying beds. Water plant sludge too can be dewatered in this fashion. Air drying of sewage sludge is more or less restricted to well digested sludge because raw sludge is odorous; it attracts insects and it does not dry satisfactorily when applied to sand beds at reasonable depths. Oil and grease discharged with the slimy raw sludge clog the sand bed pores and thereby seriously retard drainage.

Parameters - The design and use of drying beds are affected by many parameters such as: (1) weather conditions, (2) sludge characteristics, (3) land values and proximity of residences, (4) use of sludge conditioning aids, and (5) subsoil permeability.

Climatic conditions are most important. Factors such as amount and rate of precipitation, percentage of sunshine, air temperature, relative humidity, and wind velocity determine the effectiveness of air drying. Weather, being uncontrollable, prevents the establishment of a reproducible scientific dewatering procedure.

Drying on sand beds occurs by drainage and evaporation. Studies in England showed that the proportion of water removed by drainage varied between 22 and 85 percent of the total sludge moisture(221). Factors considered to be significant in drainage are sludge dewatering characteristics and the initial solids concentration of the sludge. The higher the initial water content, the larger the percentage of water removed by drainage(213).

Swanwick stated that 85 percent of the water lost from secondary sludge is lost by drainage(13). He believed that drainage was influenced by sludge characteristics and bed loading rates. Vogler and Rudolfs estimated that 60 percent of the sludge water is free or drainable, 35 percent is capillary or occluded water, and 5 percent is combined or bound water that must be removed by heat(224).

No matter which drainage figure is used, it is apparent that evaporation is also important and, therefore, so is climate. Sludge exposed to air dries to a moisture content that depends on the temperature, wind velocity, and relative humidity of the air in contact with the sludge(5). Evaporation is particularly important one to two days after sludge is applied to beds because most of the drainage is completed by that time. After a few days the sludge cake shrinks horizontally producing cracks at the surface which accelerate evaporation by exposing additional sludge surface areas(2). Cracking also enhances drainage. While rain lengthens the drying time, its effect is less important if the sludge has dried to the point of cracking. In addition to lengthening the drying time, excessive rainfall on a drying sludge has a secondary disadvantage of reducing the sludge fertilizer value because soluble nutrient compounds are removed(8).

The effect of temperature on the rate of drying has been well established. Quon and Ward reported that the evaporation rate doubled when converting from a low temperature-low humidity environment for sludge drying to one of high temperature -- high humidity(217). Fleming stated that sludge dries in 6 weeks during the summer but requires 12 weeks to dry in the winter(48). In England, average sludges dry in 1 to 3 months during the summer, but in the winter, 6 months or more may be required(70). Records from Birmingham, England, show that the summertime sludge drying rate was three times greater than the winter rate(289). Because temperature is so important, many operators of wastewater treatment plants store sludge in digesters during the winter and apply it to drying beds only from April to September.

More favorable conditions for drying may be created by covering drying beds and providing artificial heat. These modifications will be discussed in the following design section. Alternate freezing and thawing of sludge encourages dewatering, therefore, disposal plants in cool climates could operate drying beds throughout the year.

The nature and moisture content of the sludge discharged to drying beds affects the drying process. Sludges containing grit dry fairly rapidly, those containing grease more slowly; aged sludge dries slower than new sludge; primary sludge dries faster than secondary sludge; and digested sludge cracks earlier and dries faster than fresh sludge(70). It is important that sewage sludge be well digested for optimum drying. In well digested material, entrained gases tend to float the sludge solids while leaving a layer of relatively clear liquid that readily drains through the sand(2). However, Haseltine reported that sludge can also be "over-digested" causing a reduction in the drying rate(209). The more water removed by drainage, the less is required to be removed by evaporation; the overall effect is reduced drying time.

Vogler and Rudolfs determined the effect of initial solids concentration on sand bed dewatering by studying paper mill white water sludge in the laboratory(224). Figures 14. - XXIII, XXIV and XXV depict the results of their experimentations. Note that the percentage of drainable water in the total sludge water decreased on a straight line basis as the sludge solids concentration increased. Also, drainage time increased as the solids concentration increased, therefore, the lower the initial solids, the more rapid is the drainage. The final cake moisture in the dried solids increased again as the solids concentration increased. Therefore, the lower the initial solids concentration, the more complete is the drainage.

Design-Standard - Most drying beds are open and completely exposed. Others are glass covered to reduce the effects of weather on the drying process.

The "10 States' Standards" and Seelye design criteria for drying bed size recommend the following(1, 2):

Size of Digested Sewage Sludge Beds for an Area
40° and 45° N Latitude

| Type of Sludge | Bed Area in Sq. Ft./Capita<br>Open Beds | <br>Covered Beds |
|---|---|---|
| Primary | 1.00 | 0.75 |
| High-rate trickling filter | 1.50 | 1.25 |
| Activated sludge | 1.75 | 1.35 |

Figure
14.XXIII

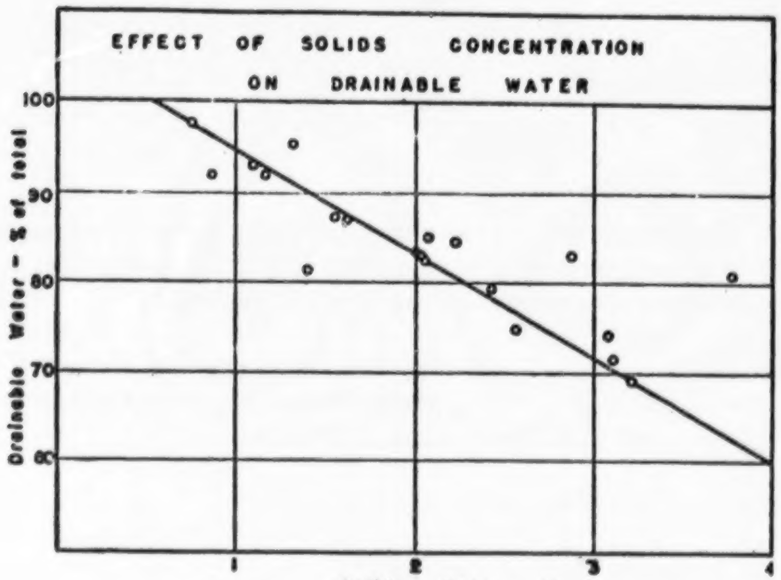


FIGURE 1.

Figure
14.XXIV

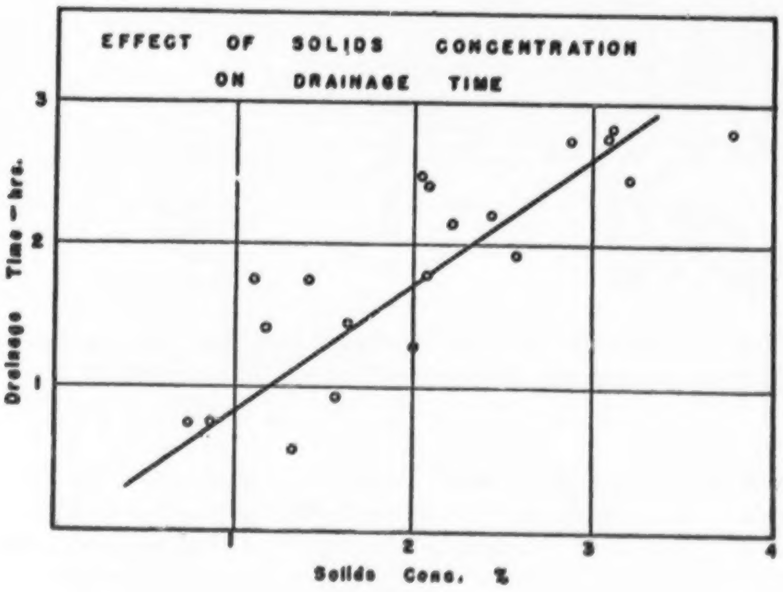


FIGURE 2.

Figure
XXV

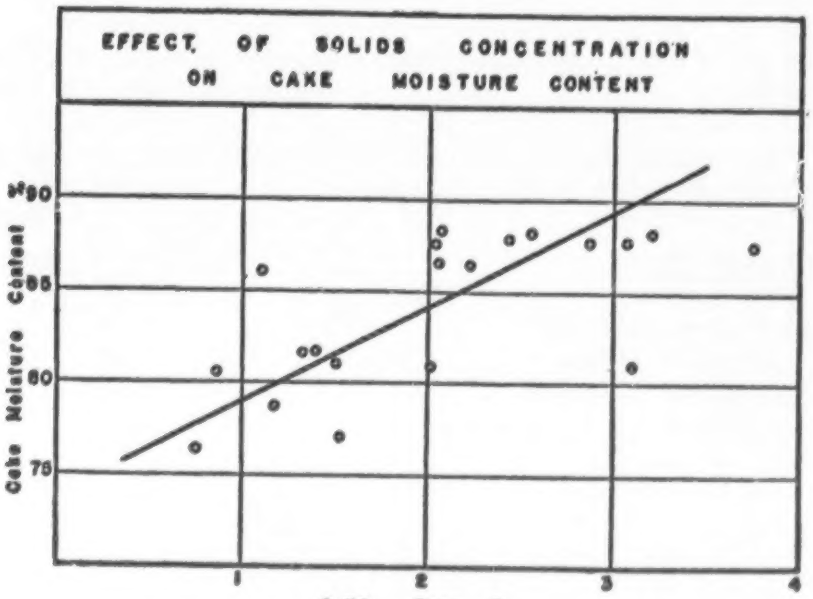


FIGURE 3.

(Reprinted by permission Schools of Engineering, Purdue University)

Areas south of the standard latitude can reduce the recommended bed area by 25 percent while areas north of this latitude should increase the above recommended areas by 25 percent.

Design standards, formulated by the Texas State Department of Health, for the area required for drying were based on rainfall and relative humidity(3). They use the following formula:

$$\text{area in sq. ft./capita} = 0.01\ R + F$$

R = average annual rainfall

F is related to humidity as specified in the following chart:

| Average annual relative humidity (based on average readings taken at 6:30 AM and 12:30 PM) | F |
|---|---|
| $<60\%$ | 0.3 |
| 60-70% | 0.5 |
| $>70\%$ | 1.0 |

The drying bed area selected by the "Texas formula" would be very similar to that recommended by Seelye and the "10 States" Standards."

Other specific design standards have been discussed in the literature. Furman said only 0.3 square feet per capita for drying bed area was required in semi-tropical climates such as Florida. His conclusion was based on the drying of digested primary sludge and trickling filter humus(26). Ryan recommended the following criteria for northern (cool) areas(212):

| | |
|---|---|
| Open beds operated 6 months/year | 0.6 to 0.8 sq. ft./capita |
| Covered beds | 0.2 to 0.3 sq. ft./capita |

In England, the following capacities have proven to be adequate for normal sludges under normal climatic conditions(70):

| Sewage Sludge Type | Sq. Ft./Capita (Open Beds) |
|---|---|
| Primary sludge | 1.30 |
| Trickling filter sludge | 1.50 |
| Digested mixed sludges | 1.00 |
| Undigested mixed sludges | 2.25 |
| Sludges inclined to be greasy | 3.00 |

English standards for covered beds are one-third less than the area recommended for open beds. Zack stated that glass covered beds required 30 to 50 percent less area than open beds(28).

Another criteria for the design of sand beds could be pounds of dry solids per square foot per year. Fischer recommended the following digested sewage sludge bed loadings based on actual plant operation data(57):

| | Lbs. Dry Solids/Sq. Ft/Year | | | |
|---|---|---|---|---|
| | Primary Sludge | Primary + Filter Humus | Primary + Activated | Activated |
| Open beds | 35 | 30 | 30 | 25 |
| Covered beds | 70 | 60 | 60 | 50 |

Somewhat lower values were presented by Eckenfelder and O'Connor for open beds to dry sewage sludge(5):

| Type of Digested Sludge | Area Sq. Ft./Capita | Sludge Loading Dry Solids Lbs./Sq. Ft./Year |
|---|---|---|
| Primary | 1.0 | 27.5 |
| Primary and standard trickling filter | 1.6 | 22.0 |
| Primary and activated sludge | 3.0 | 15.0 |
| Chemically precipitated sludge | 2.0 | 22.0 |

Drying beds usually consist of 4 to 9 inches of sand over 8 to 18 inches of graded gravel or stone(1, 2, 5). The sand has an effective size of 0.3 to 1.2 mm and a uniformity coefficient less than 5.0. Gravel is normally graded from 1/8 to 1.0 inches. Drying beds are drained by underdrains spaced from 8 to 20 feet apart. Underdrain piping is often vitrified clay laid with open joints, having a minimum diameter of 4 inches and a minimum slope of about 1 percent. Collected filtrate is usually returned to the treatment plant.

Ideally, the applied sludge should be well distributed in the drying bed or uneven loading rates will occur. A 5 percent sludge, for example, may not travel more than 50 feet due to its relatively high viscosity, which increases as it dewaters. At the Maple Lodge Works in England, rapid distribution of sludge is achieved because each drying bed has 32 sludge application points(223). The end of the application pipe should not be submerged and splash plates should be used to distribute the sludge more evenly.

As indicated in the design criteria, the use of covers reduces the required area for drying beds. Bed enclosures, usually glass, protect the drying sludge from rain; they help control odors and insects; they reduce the drying periods during cold weather; and they can improve the appearance of a waste treatment plant. Fair and Geyer stated that if the enclosures are properly ventilated, the number of sludge applications per bed can be increased from 33 to 100 percent over beds without covers(7). Good ventilation to reduce humidity is important because enclosures restrict air circulation, resulting in reduced evaporation. As expected, evaporation is more rapid from open beds in warm fair weather, but, during rainy or cold periods, evaporation from covered beds is faster.

In England, many engineers have believed that covered beds are over-rated. Swanwick and Baskerville believed that covering of beds is useful only when there is a requirement to dewater sludge beyond the minimum required for lifting. Also, they believed that covering would be useful in areas of very high rainfall(221).

MacLaren predicted that covered beds will be used less and less due to difficulties involving the maintenance of mechanical equipment(53). Adapting mechanical equipment to a relatively small enclosure is more difficult than with open drying beds. The suggestion has been made to combine open and closed beds(3). This system would offer flexibility for varying weather conditions and have the advantages and disadvantages of both types of drying beds.

Design-Modifications - Some drying beds have been constructed with asphalt or concrete bottoms to facilitate removal of the dried sludge. These beds seem to function well in areas where evaporation rates are high(8).

Lynd described an asphalt bed where 3 inches of asphalt, rather than sand, were placed over a base-layer of gravel(208). He reported that the advantages were: reduced drying time and less maintenance. Twelve beds at Salt Lake City, Utah, were paved with asphalt; result was that reduced equipment, operation, and maintenance costs saved $84.50 each time a bed was filled(66). At the Maple Lodge Works in England, a 2-1/2 inch water-tight asphalt layer was placed beneath layers of gravel and fine sand to prevent pollution of underlying water-bearing gravel(223).

Grove concluded that concrete-bottom drying beds take twice as long to dry sludge as sand beds, but the labor cost is much less(215). Particularly, rain caused problems due to the limited drainage area installed at the center of the bed. Because power equipment could be used to lift dried sludge off the beds, it took one-seventh the time to clean the concrete bed as it did a conventional sand bed.

In England, bed media have consisted of clinkers with a top layer of fine ashes(70). Comparative performance data from the use of unsolidified media other than sand and gravel have not been reported.

Heating sand drying-beds, particularly the glass-enclosed type, have shortened the drying time. One theory suggested that the heat accelerates sludge biological decomposition, producing gas which floats the sludge solids and allows the water to drain away(221). Heat also decreases the sludge viscosity causing it to drain more rapidly. At Durham, North Carolina, heating coils, placed on 5-inch centers in covered drying beds, greatly increased the drying capacity(211). The heat was supplied by circulating cooling water from gas engines through the coils.

Wedge-wire drying beds have been used in England with great success. They consist of a perforated sheet laid on top of conventional drying bed media(62). "Support water" is first added to the drying bed to prevent blinding of the media when sludge is added. As the sludge is applied and forms its own filtering layer, the support water is slowly removed. This procedure prevents solids from breaking through the wedge wire and plugging the drying bed. Advantages claimed for wedge wire beds include: (1) no clogging of the media, (2) constant and rapid drainage, (3) increased bed capacity because more loadings are possible, (4) easy bed maintenance, (5) easier dried-sludge removal, (6) less susceptibility to adverse weather, and (7) difficult-to-dewater sludges can be dried(62, 181, 218). Lewin quoting Stokes and Harwood reported that the following difficult sludges can be dewatered: hydroxide sludge, bacterial slimes, vegetable wastes, slag fines, and tannery sludges(62).

Frequently, sludges, applied to drying beds, are conditioned with chemicals or other materials. An increased rate of drying is the major advantage sought in the use of conditioning aids. This advantage is very important when an inadequate drying area is available, when the sludge has poor drying characteristics, or when unfavorable weather threatens to delay the drying process. In addition to increasing dewatering rates, conditioning aids reduce sand-bed maintenance because uniform sludge drying throughout its depth permits more complete removal of cake from the sand.

Materials used to condition sludges have included inorganic flocculents, polymeric flocculents, sawdust, sulfuric acid, anthracite, and activated carbon. Alum and aluminum chlorohydrate have been particularly popular as conditioning aids in England. These aids make a sludge more porous which allows more rapid and uniform dewatering. They also improve the structure of the sludge solids, thereby decreasing solids compression and subsequent media blinding.

Mechanical facilities to assist dried sludge removal can be a solution to one of the biggest disadvantages of sand drying beds, the availability and cost of labor. Mechanical lifting of sludge has been practiced for many years at some large treatment plants, such as Chicago, but now it is receiving more attention as the need to minimize labor costs grows.

Kershaw reported that machine lifting and conveying of sludge at Maple Lodge, England, has been successful for two reasons: (1) it decreases labor costs and (2) it effectively increases the drying capacity of the system because dried sludge can be removed faster, allowing the beds to be filled more frequently(223). The equipment consisted of adjustable tines that lifted the sludge from the sand, a flight-elevator fed by rotating crocodile-toothed paddles, and conveyor belts that transferred the lifted sludge to a storage area. The main sludge-lifting equipment rides on rail tracks placed on top of drying bed dividing walls. Other interesting features of the lifting unit include equipment for scraping off excess sand from the bottom of the lifted sludge cake, disc harrows to agitate the drying bed surface, and equipment to level the sand surface after lifting so that the beds can be immediately refilled.

In lieu of mechanical lifting, the dried sludge is usually forked or shoveled into wheelbarrows or trucks. The ideal situation, however, is probably one where the treatment plant operator convinces the public to fork their own sludge and carry it away after shredding.

Operations - Sand bed operations are more of an art than a science because of the large number of uncontrolled variables. When sludge is first applied to a drying bed rapid drainage occurs, but soon the hydrostatic pressure of the sludge draws sludge solids into the sand and compresses the layer of sludge in immediate contact with the sand. Eventually the drying bed becomes spongy and resists liquid flow, so evaporation has to complete the drying process. The operation is necessarily intermittent because dried sludge is almost always removed before more sludge is applied.

Sludge is normally applied to a drying bed at a depth of 8 to 12 inches. This varies at different locations depending on the sludge characteristics, weather, rate of drainage and method of sludge removal. Bowers believed that the lower end of the range is advisable because the water drains better, there is less chance of sealing the sand with sludge particles, and the sludge cracks faster than it does if 10 to 12 inches are applied(207). Digested secondary sludges are applied at depths less than that of primary sludge.

VanKleeck said that the wet-sludge drying time is increased by each inch of additional sludge depth and also by increases in the dry solids concentration. As an example he presented this data:

5% solids sludge dries in one week of good drying weather
8% solids sludge dries in two weeks of the same weather(8, 12).

Figures 14.XXVI and 14.XXVII also show the importance of sludge depth(224). Drainage time and cake moistures measured after 24 hours increase as the depth of applied board-mill sludge is increased. Data from England showed the following relationships between sludge depth and drying time(289):

18 inch depth, one bed loading dried in 203 days
12 inch depth, two sludge applications of 12 inches each, dried within 203 days
6-9 inch depths, three sludge applications of 6-9 inches each, dried within 203 days.

Observing drying bed performance and applying a reasonable sludge depth to promote the most efficient use of the beds appears to be good advice.

MacLaren recommended that the optimum solids loading of drying beds was 15 pounds (dry) per square foot for uncovered beds and 25 pounds

Figure 14.XXVI

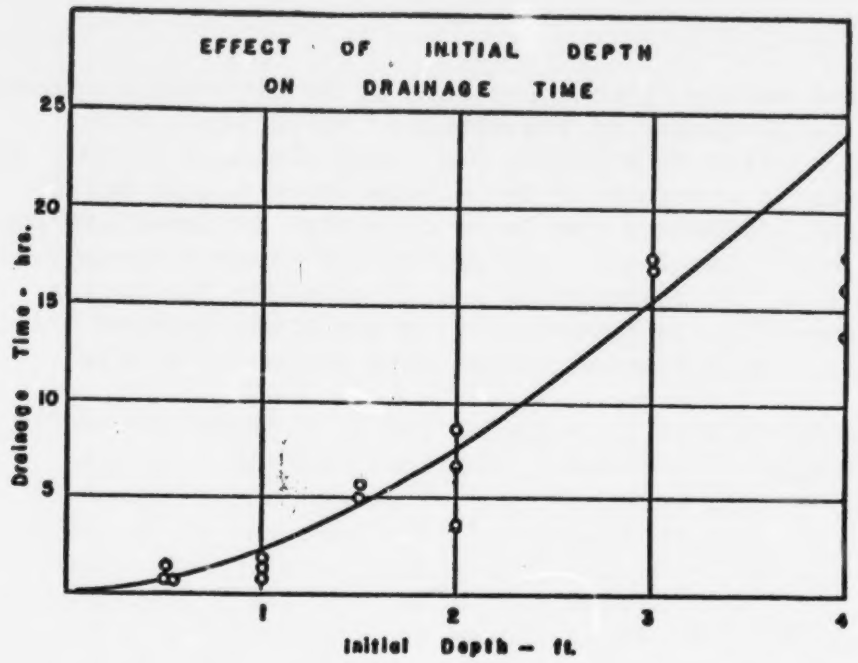
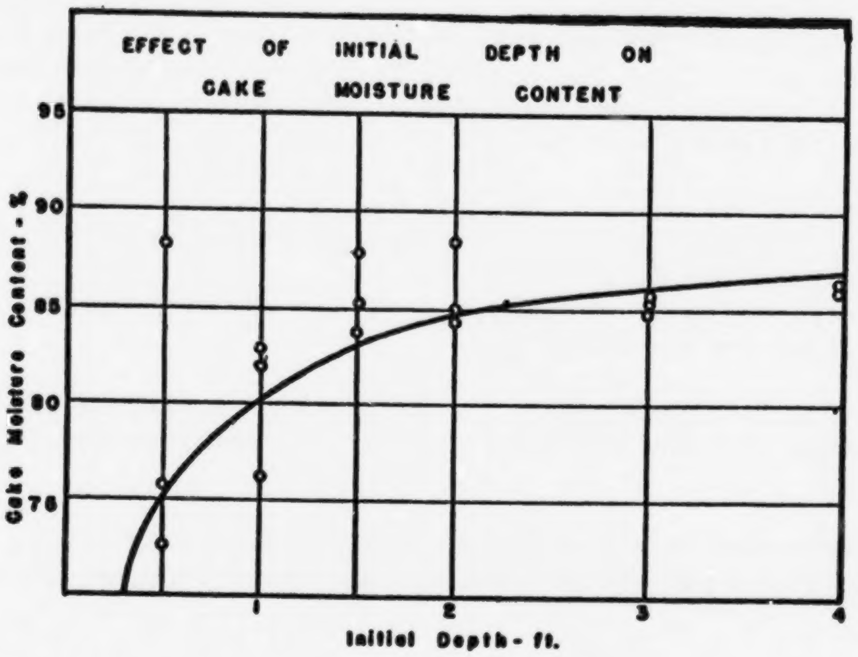


Figure 14.XXVII



(Reprinted by permission Schools of Engineering Purdue University) per square foot for glass covered beds. The first loading applies to seven fillings per year, the second to twelve times per year(53). Uniform solids loading over the entire bed is encouraged by multiple application points. This technique, while not commonly designed into a system, could significantly increase drying bed efficiencies.

Pilot plant investigations in England proved the usefulness of decanting and sludge elutriation for most efficient use of drying beds(221). Decanting the easily separated sludge water puts less of a demand on the drainage system. Elutriation improves the drying rate of sludge probably because it removes the fine solids that have a tendency to seal the sand bed. The technique used in England and described for wedge-wire beds, which included "support water" applied by flooding the bed above the sand surface, before sludge is added, is also recommended to prevent sand-bed sealing(221).

Filling the beds when rain or cold weather is not expected is recommended for rapid drying. A heavy rain beating on the sludge can seal voids at the sand surface and thereby retard drainage. Once cracks are formed the effects of rain are minimized. Cracking often occurs within 2 days in the summertime(223).

The solids content at which various sludges reach a "liftable" state differs considerably (state at which sludges are removed from the drying beds). Many references cite 50 percent solids as the normal liftable state. In England, 55 percent solids is considered liftable for badly drained sludge, but 16 percent solids is considered liftable for a well drained sludge because it dewaters more uniformly(221). Sludges that require extensive drying before removal reduce the efficiency of drying beds.

After the dried sludge is removed by manual labor or machine, the drying beds require maintenance. Small sludge particles and weeds should be removed from the sand surface. Periodically the bed should be disced and the top layer of sand replaced. Usually resanding is advisable when 50 percent of the original sand depth is lost(8).

Sludge dried to at least 70 percent moisture is often hauled to landfill sites or used as a soil conditioner. Weathering of the dried sludge makes it friable and, therefore, more suitable for spreading. In Dayton, Ohio, drying-bed sludge was heat-dried to less than 10 percent moisture, bagged, and sold as fertilizer(374).

Sludge dried on open beds probably never attains this level of dryness. Shredders have often been installed at drying bed sites to make the sludge more appealing for soil conditioning purposes. Some beds have been kept open to the public in the hope that the sludge will be shredded and hauled away "free-of-charge" by the taxpayers.

An analysis of plant records has shown that few drying beds are utilized at full capacity. Their capacity depends upon the bed area, maintenance, weather conditions, sludge characteristics and the moisture content of the "lifted" sludge. The following good operational techniques enhance efficient utilization of bed capacity:

1. A properly digested sludge is essential for good dewatering. The digesters should be operated to produce a sludge that dries rapidly.
2. A clean bed with porous, level, and loose media should be available for each sludge filling.
3. Beds should not be filled during periods of rainfall and low temperatures.

Performance - A typical curve describing sludge drying on sand beds during warm weather shows rapid dewatering for 1 or 2 days (drainage) followed by a 2 to 5 week period of slow dewatering (evaporation).

MacLaren said that a well digested sewage sludge dewaters from 95 percent to about 55 percent in 6 weeks of good weather if applied at a depth of 6 to 9 inches(53). English observers believed that many industrial sludges dewater better on sand beds than do sewage sludges(225). Vogler and Rudolfs after testing paper mill sludges, confirmed this belief because board-mill sludge drained a little faster than sewage sludge(224). They believed that the effectiveness of dewatering paper-mill white-water sludge on a drying bed depends on the raw materials used, the mill operations, and the particular "saveall" process. Variations are expected because paper mill sludges will have different concentrations of fiber, filler, sizing, and cellulose debris.

Studies of the performance of open versus covered drying beds showed inconsistent results. However, covered beds can be expected to handle a higher solids-loading rate because they can be filled more frequently than open beds.

The literature contains many reports showing that drying-bed performance can be greatly improved by conditioning the sludges with chemicals and other materials before their application to the beds. Sperry made the following conclusions concerning the use of chemicals to treat sewage sludge prior to sand bed dewatering at Aurora, Illinois(188): (1) alum is the most effective and economical sludge conditioning agent, (2) all trivalent iron salts are effective flocculating agents but they should not be used because iron oxides plug the pores, and (3) for sludges containing less than 3 percent solids, alum dosages of 1 pound to 200 or 300 gallons of sludge are recommended.

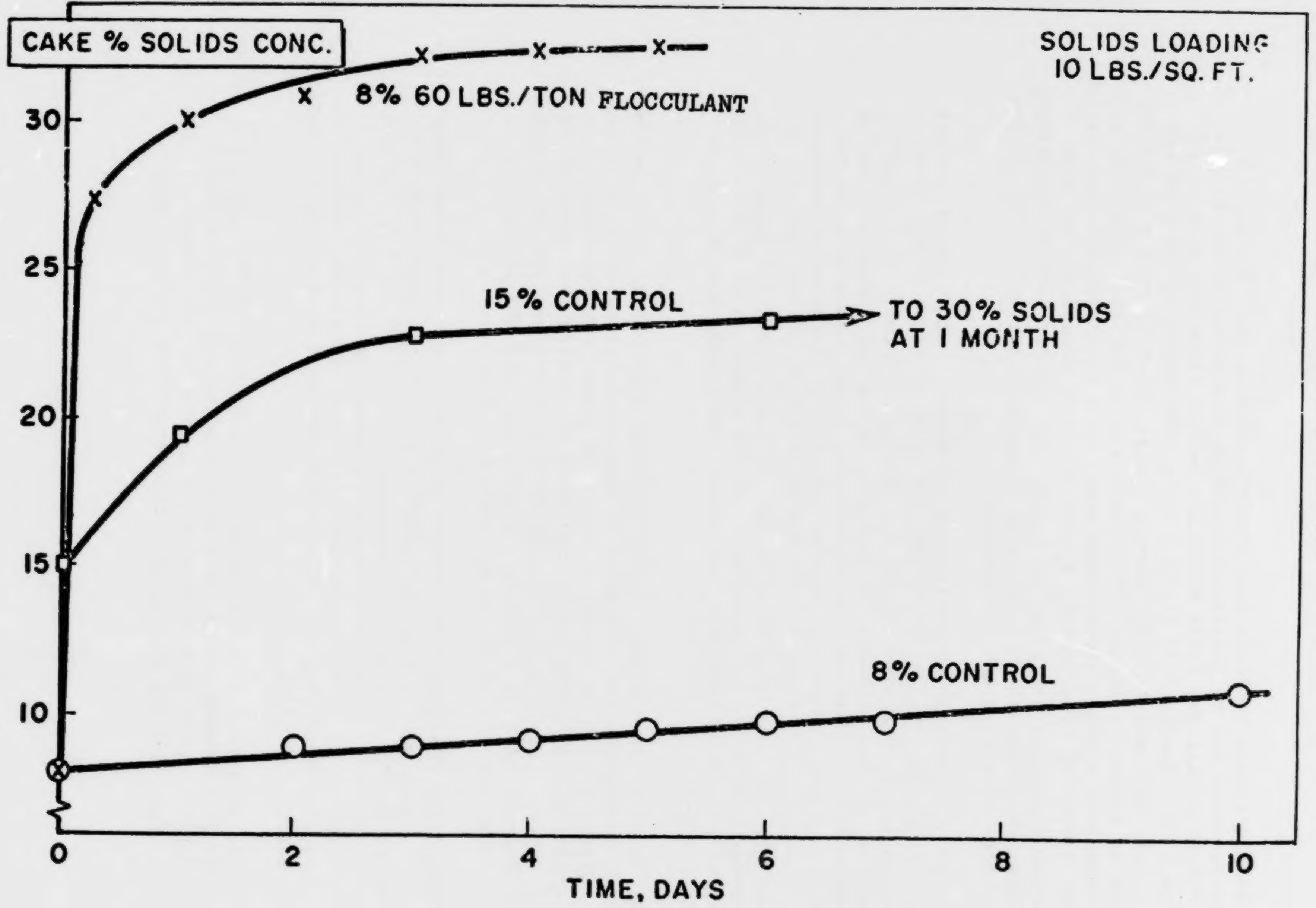
After a scientific investigation at Butler, Pennsylvania, it was concluded that the greatest benefit from chemical sludge conditioning is realized during the months of October to December. Little, if any, benefit is realized during the summer and spring months(209). VanKleeck stated that 6 to 10 pounds of alum per 1,000 gallons of sludge improve the drying character of normally slow-to-dewater sludge(12). The WPCF Manual of Practice No. 11 recommended that alum at a dosage of 1 pound per 100 gallons of sewage sludge should be mixed with the sludge as it flows to the beds(11). Alum treatment may reduce the sludge drying time by 50 percent.

At Tenafly, New Jersey, ferric chloride was determined to be the best flocculent for conditioning sewage sludge prior to sand bed dewatering(32). A dosage of about 90 pounds per ton (dry) permitted the removal of sludge from the drying bed after 10 to 20 hours. The thin feed sludge (0.5 to 0.75% solids) was applied at a depth of 8 to 9 inches. A liftable cake was produced at a moisture content of 87 to 89 percent solids.

Kelman and Priesing have presented interesting pilot plant data showing improved drying-bed performance after conditioning the sewage sludge with organic polyelectrolytes(198). They claimed that polymeric flocculents could increase the rate of bed dewatering up to 30 times the rate of conventional bed performance. Unprecedented drying bed yields were obtained by loading the beds to depths exceeding 3 feet.

Figure 14.XXVIII from the Kelman-Priesing report(198) shows a greatly increased drying rate with sludges conditioned with a cationic polymer at a dosage of 60 pounds per ton (dry). It was concluded that the drying bed yield increases linearly with

Figure 14.XXVIII



TYPICAL DRYING DATA-CONSTANT SOLIDS LOADING

(Courtesy of The Dow Chemical Company(198)) increasing polymer dose. This is described in Figure 14.XXIX(198) for a number of different drying periods. Depths of applied sludge up to 6 feet were studied in contrast to the normal 8 to 12 inch depths. It was observed that dewatering was retarded up to a depth of 3 feet, but beyond that depth, no further retardation occurred and, of course, the yield increased. Beyond 3 feet, the drying rate was identical for all depths. Figure 14.XXX(198) describes the relationship of extraordinary depths with time and cake moisture when the sludge is conditioned with 60 pounds per ton of polymeric flocculent. It was noted that unconditioned sludge stored in lagoons 2 to 6 feet deep may require several months to a year to dry satisfactorily, as compared to the few days required for the conditioned sludge.

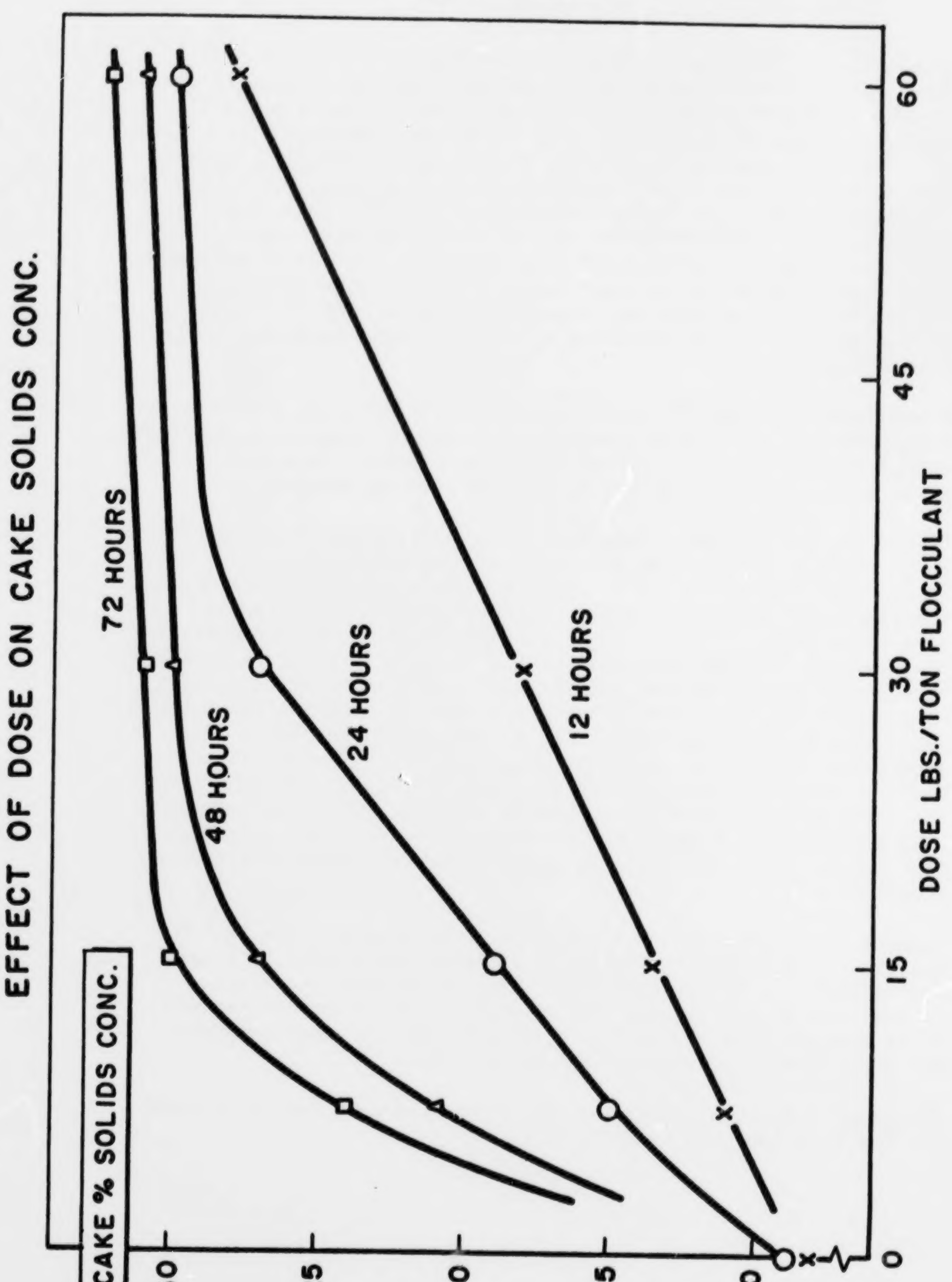
Kelman and Priesing(198) believed that dewatering was essentially a filtration process with evaporation being of secondary importance, except for the top 2 inches of the sludge layer. Rain, even in the early drying stages, did not retard the rate of dewatering.

Figure 14.XXXI presents data from an actual sewage plant operation where organic polyelectrolytes were used to condition sludge prior to sand-bed dewatering(199). Upon loading at conventional depths, the chemically treated sludge exhibited greater increases in dewatering than the control. A good solution to the supernatant disposal problem was indicated by the data(199) in Figure 14.XXXII. Supernatant liquor can be rapidly dewatered on drying beds, after treatment with 2.8 to 4.5 pounds of a cationic polymer per 1,000 gallons of supernatant liquor (66 to 106 pounds per ton). The supernatant liquor was applied to a depth of 18 inches; after 12 days the material treated with a polymer dosage of 106 pounds per ton had a solids concentration of 51 percent. Polyelectrolytes have also been evaluated in England where researchers concluded that they promote bed cracking and, therefore, speed up evaporation(218).

Ullrich and Smith mixed 3.5 cubic yards of sawdust with 10,000 gallons of digested sludge before applying the sludge to a sand drying bed(377). They concluded that, by keeping the sludge porous, the sawdust allowed the sludge solids to dry faster and to be removed from the beds 1 to 3 weeks earlier than expected. The sawdust also eliminated offensive odors.

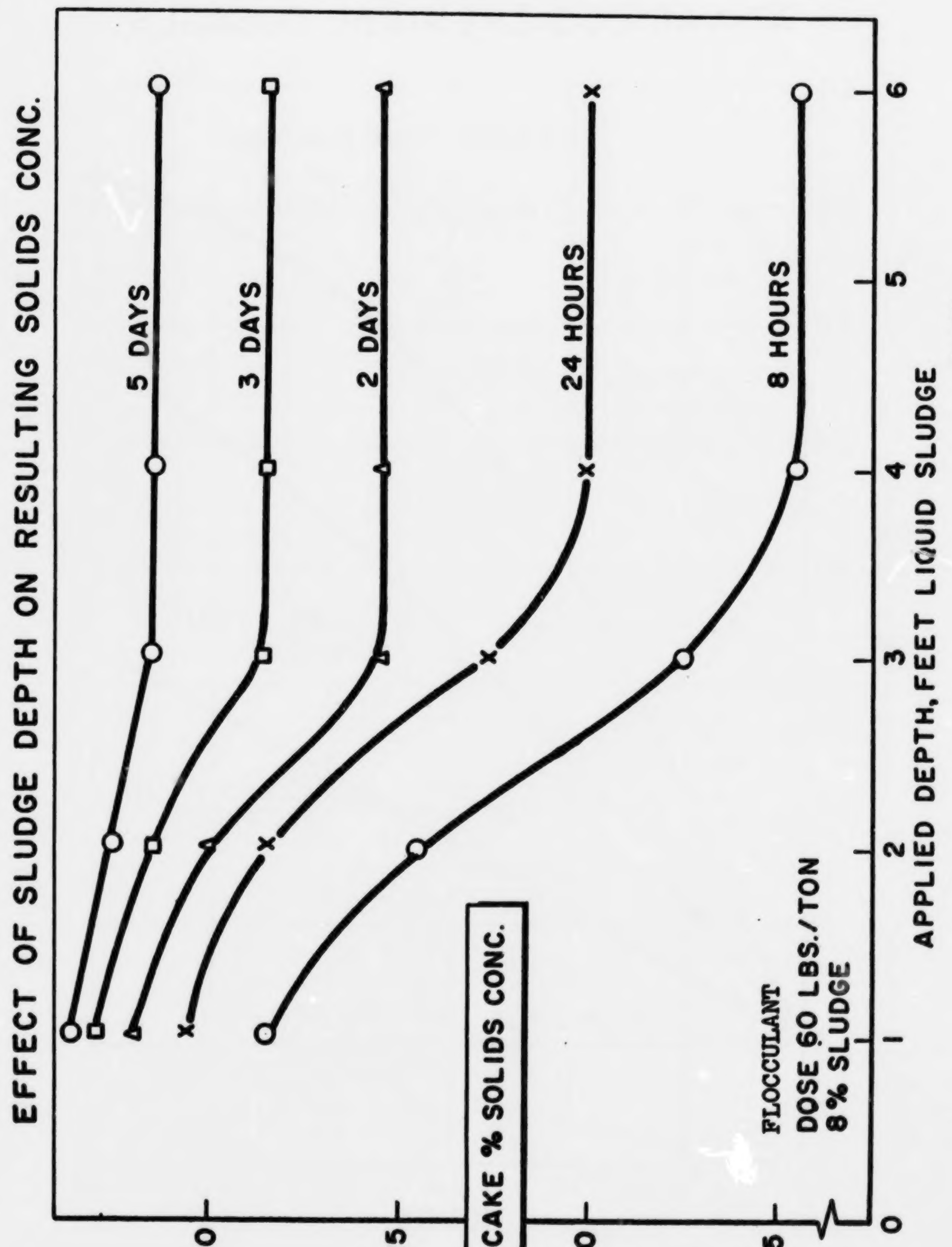
Economics - MacLaren estimated the cost of drying beds in Canada for the year 1961, as follows(53):

Figure 14.XXIX



(Courtesy of The Dow Chemical Company[198])

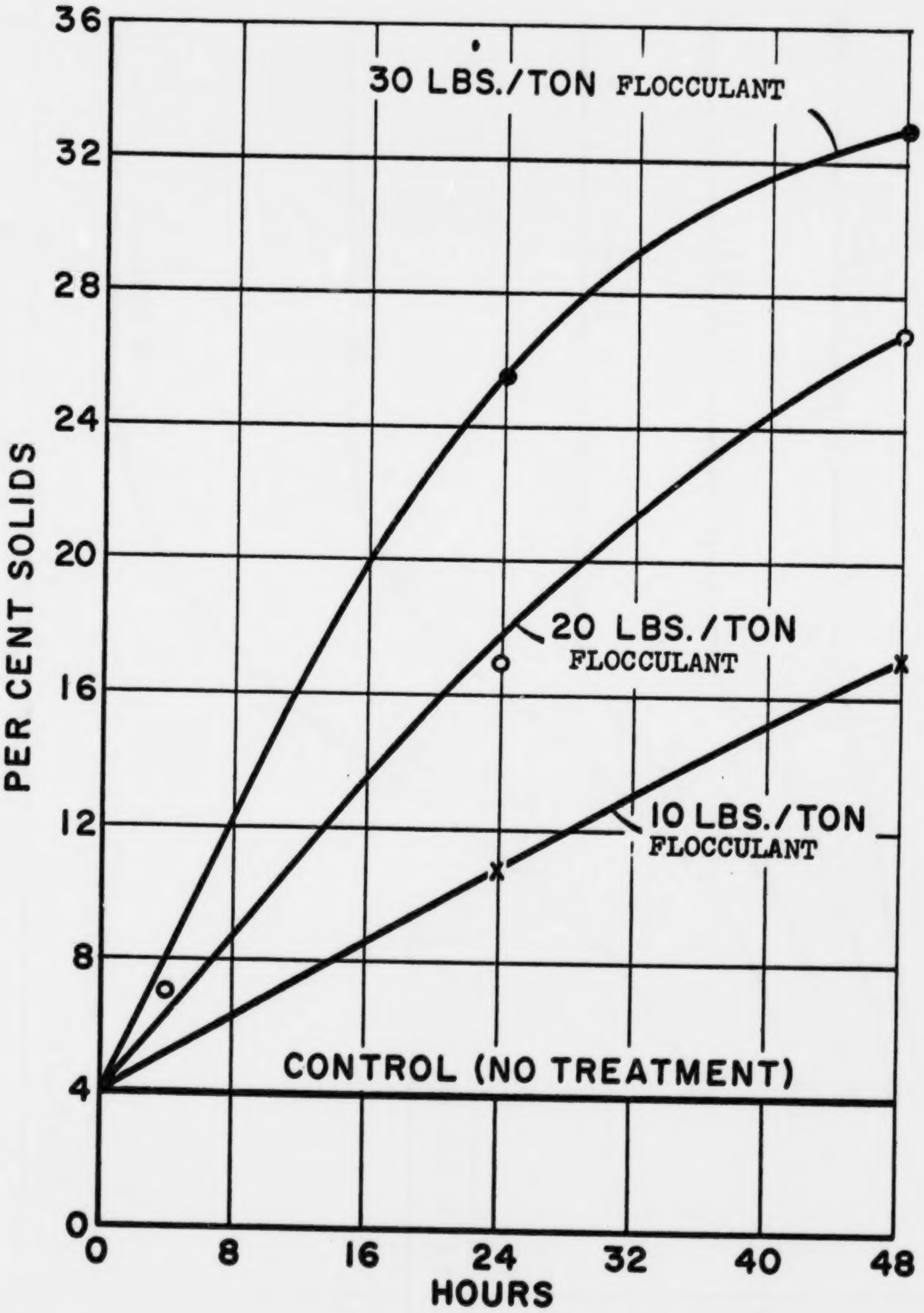
Figure 14.XXX



(Courtesy of The Dow Chemical Company[198])

Figure 14.XXXI

## DIGESTED SLUDGE DEWATERED ON SAND DRYING BEDS AT VARIOUS CHEMICAL DOSAGES

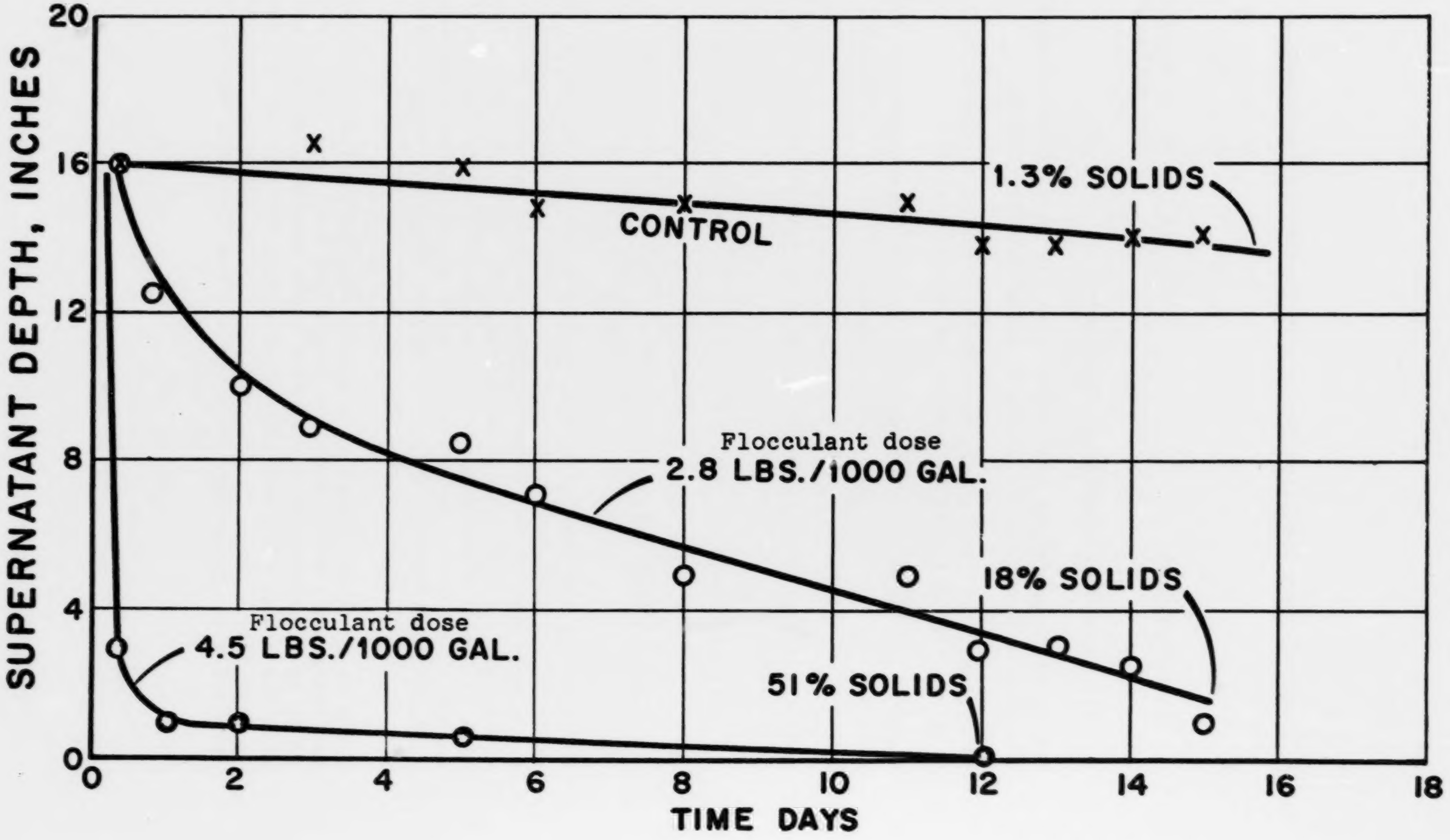


(Courtesy of The Dow Chemical Company(199))

TREATMENT OF SUPERNATANT ON DRYING BEDS
SOLIDS LOADING: 18 INCHES OF 1% SUPERNATANT

Figure 14.XXXII

(Courtesy of The Dow Chemical Company[199])



Capital cost installed for 10,000 Population Equivalent =
$0.25/sq. ft. or
$2.65/ton

Operating cost = $1 to $10/ton of
dry solids removed

(30 years amortization at 5% interest)

The specific operating cost depends on the local labor situation and the hauling costs to the ultimate sludge-disposal point.

In England, the 1963 annual cost for dewatering sludge on drying beds was $11.90 to $19.60 per ton of dry solids(218).

In 1966, an estimated cost for constructing concrete-bottom drying beds was $0.80 per square foot. The cost of asphalt beds would probably be similar(215).

Seelye's design manual listed the cost of conventional drying beds as follows(71):

| | |
|---|---|
| Open sand beds | $0.94/sq. ft. or $1.15/sq. ft. at January 1, 1966 costs |
| Glass covered beds | $2.05/sq. ft. or $2.50/sq. ft. at January 1, 1966 costs |

Kershaw reported very high construction costs for the drying-bed at Maple Lodge Works in England(223). The bed itself cost $2.62 per square foot or $4.70 per square foot when the cost of the mechanical lifting and conveying equipment were included. The high bed costs were probably due to adverse weather conditions and the need to protect ground water by incorporating an impervious asphalt layer beneath the sand. Annual operating costs of $76.45 per ton (dry) were reported for the year 1963-1964(223).

The sale of dried sludge as a soil conditioner offsets the drying bed operating costs. Shredded sludge has been sold for as much as $6 to $10 per cubic yard. Many waste treatment plants, however, give the sludge away and thereby eliminate the cost of hauling it to land-fill sites. In general, the capital and operating cost for dewatering sludge on sand beds varies from $3 to $20 per ton of dry solids applied. Digestion before dewatering significantly increases the total sludge-disposal process cost. A typical value for digestion plus sand bed dewatering would be $25 per ton.

Summary - Sand drying beds will continue to be a useful and common tool for sludge dewatering. As reported by Chambers,digesters plus sand beds are the most economical dewatering technique for sewage treatment plants serving cities with flows less than 10 mgd, when compared with vacuum filtration or raw sludge filtration with subsequent incineration(58). MacLaren believed that rising labor costs restrict the use of sand-drying beds to cities having less than 5,000 people(53). The "10 States' Standards" stated that sand beds are in common use at small to medium-sized plants, particularly where land is inexpensive and where a demand exists for the sludge as a soil conditioner(2).

The popularity of sand drying beds cannot be disputed. They are popular first because of economics. Only sludge lagoons, ocean disposal, or liquid sludge disposal to nearby land are generally considered to be less expensive than sand bed dewatering. A second reason for their popularity is simplicity. Sludge beds can be filled and essentially forgotten until the sludge has dried. This is a major factor in the acceptance of drying beds by smaller communities and some industrial plants.

Sand drying beds have, however, certain disadvantages. These include: (1) the area required, (2) potential nuisance problems, (3) cost of removing the sludge, (4) susceptibility to adverse weather conditions, and (5) the general need for a digestion step preceding sand bed dewatering.

The area requirement often eliminates drying beds as a practical technique for large municipalities. However, there are still a few large cities using beds for at least a portion of their sludge dewatering needs. Obviously the local situation in each case will determine the suitability of using drying beds.

Digesting organic sludges before sand bed dewatering reduces the potential threat of nuisance conditions. Sewage sludges are almost always digested before drying on sand beds, but digestion is not often specified for industrial sludges. Lime may be added to organic sludges to control odors, but it has a tendency to plug sand pores and thereby retard drainage.

The labor cost of lifting dried sludge from beds can be substantial because it takes a few days to remove sludge from a medium-sized bed. Improvements in mechanical lifting and sludge conveying equipment could make the economics of drying beds much more attractive at medium to large-sized treatment plants.

The climate (rainfall, temperature, and humidity) is the most important factor in sand bed dewatering. It cannot be very well controlled, even though rainfall can be eliminated by covering the beds with glass structures. Rain interferes with drying and bed cleaning; however, the specific effect has not been determined because it depends on the state of sludge dryness at the time of precipitation. But, the normal, covered bed is expensive, it does not prevent freezing, and it is very hot to work under when cleaning beds during the summer months(23). In northern climates, drying beds are generally not used from November to March unless the beds are covered. Sludge storage for 3 to 5 months, usually in digesters, is an additional expense.

Future sand bed designs should consider decanting facilities; decantation can remove a significant part of the total water contained in sludge and can therefore increase bed capacities. Other process improvements may result from the use of chemicals or heat and from the installation of mechanical lifting equipment. Consideration should be given to transporting liquid sludge through pipelines to rural areas where the sand bed drying process would be more suitable for many reasons.

## E. Screening

General - Dewatering of sludge on vibrating screens has been investigated in a number of sewage treatment plants in the United States. Overseas, there are more than 20 sewage plants using the Heymann process which consists of vibrating screens followed by rotary filter presses(132). The use of screens is advantageous because of their simplicity and small size. Up to now, however, the disadvantages of screens have generally precluded their use in sewage treatment plants except for floatables and trash removal.

Design - The Rhewum (sonic) vibrating screen filter, described by Kiess and Schreckegast(128), consists basically of three screens in series. The first is a coarse screen (8 x 24 mm mesh) that removes 2 percent of the total sludge solids. Next in line is a sonic screen (1.2 - 2 mm mesh) that is vibrated by electromagnets attached to one edge of the filter cloth. Longitudinal and transverse waves are formed which agglomerate and concentrate the solids while moving them to the next screen in series. Twenty-three percent of the total solids are removed in the second step. The last screen is called a sonic filter (0.1 - 0.5 mm mesh); it also is vibrated by electromagnets. This screen removes 55 percent of the total solids. The screens are vibrated at 1,200 rpm with a double amplitude of 4.4 - 7.8 mm. Synthetic fabrics are used for coarse screening, but the finer screens may be stainless steel.

The Southwestern Engineering Company (SWECO) built a vibrating screen unit that has been evaluated in municipal and industrial wastewater treatment plants. Their "Vibro-Energy Separator" develops a variable, low amplitude, three-dimensional motion that moves sludge across a metallic screen(133). A combination of radial and tangential motions move the sludge in a long spiral path from a vertical and well distributed center feed point to an outer rim discharge. Vertical amplitude creates a vertical motion that accelerates the drainage of the liquid through the media. Sludge particles as small as 44 microns may be removed.

Operation - The efficiency of the Rhewum screen depends on the solids loading, sludge particle-size distribution, the type of sludge, and the angle of sludge discharge to the filter cloth(128). The best solid-liquid separation occurs when the sludge discharge nozzle approaches a tangential direction to the filter cloth.

Sludge fed to a SWECO screen must be at a constant rate and perpendicular to the screen surface. The three dimensional motion of the screen is regulated to form the pattern on the screen which produces the most efficient dewatering. The required pattern varies with the sludge solids concentration, the particle size distribution, and the sludge feed rate.

Performance - Sludge, having a solids concentration from 20 to 25 percent, has been produced by the Rhewum vibrating screen(128). The screen filtrate contained considerable solids but the solids seemed to have excellent settling characteristics, so it is assumed they could be handled in the primary sedimentation tanks.

Budd reported on the use of a vibrating screen and filter press at Lake Hiawatha, New Jersey(23) to dewater raw organic sludges. The combined use of a screen plus press preduced a 25 percent total solids cake from a sewage sludge having a solids concentration of 3.76 percent. Screen filtrate solids were 2 to 3 percent total solids. It was suggested that this very low solids capture would lower overall treatment plant efficiencies and, therefore, would be unacceptable.

An English reference stated that the vibrating screens, which are a component of the Heymann process, produced a filtrate containing a high concentration of solids(134). A study of the dewatering characteristics of the filtrate from the screening operation using digested primary sewage sludge as the feed, indicated that filtrate could be dried on covered drying beds in 2 to 14 days. Treating raw sludge filtrate in aeration tanks was suggested.

Studies during 1966 in California indicated that the use of cationic polyelectrolytes to condition sewage sludge prior to screening increased the efficiency of the screening process.

Economics - In Germany, the estimated cost of a complete installation including screens and a filter press for a city of 100,000 was $4.50 per ton. Operating costs were $1.35 per ton and capital costs, $3.15 per ton(66). These costs assumed that the feed sludge concentration was 10 percent. The operating costs of vibrating screens should be low if chemical conditioning of the sludge is not required. Power consumption is low and labor costs are relatively low due to the ease of operation and maintenance.

Summary - The use of vibrating screens for thickening or dewatering waste sludges is promising because the equipment is simple;

it uses very little power; the space requirement is minimal; and the screens are applicable to many different types of materials. However, screens have not been adopted for thickening and dewatering processes because of two major disadvantages; first, the solids-capture efficiency is very low; second, the degree of dewatering is unsatisfactory for subsequent disposal steps. An additional, but less basic, disadvantage is the requirement for regular screen maintenance. The screening media can be readily plugged by grease and other materials.

One of the major problems at wastewater treatment plants has been recycling of fine solids not captured by various process steps. This recycling of solids from the screening operation, or other processes, can significantly lower the overall treatment plant efficiency. Ultimate solids disposal by incineration, landfilling, or other methods often require, for practical reasons, a well dewatered material. Vibrating screens usually do not produce as high a degree of dewatering as other processes such as vacuum filtration. The use of chemicals for sludge conditioning prior to screening may eliminate the two major disadvantages; but this, of course, impairs the economic attractiveness of screens.

Vibrating screens are useful, however, for removing trash and floatables from sludge prior to ocean disposal or dewatering in other mechanical equipment. Based on available data this appears to be one of the best uses for a fine screening sludge treatment process. Industrial waste sludge dewatering is another promising use for screens. Wet solids such as paunch manure and waste tomatoes could be effectively dewatered on vibrating screens.

## 15. SLUDGE CONDITIONING AND DEWATERING UNUSUAL PROCESSES

General - To improve conventional sludge conditioning techniques, numerous unconventional approaches have been investigated. The usual research incentive is to eliminate the need for chemicals and to increase production rates.

### A. Freezing

Through the years a number of people have observed that sludge frozen by nature and later thawed in sand drying beds or lagoons had good dewatering and fertilizer or soil-conditioning characteristics. Thawed sludge was stable and dewatered rapidly if provisions were made for water drainage. These observations encouraged researchers, particularly in Great Britain, to evaluate artificial freezing of sludge as a means to promote rapid dewatering. They speculated that freezing disrupted the cell walls retaining the internal moisture in sludge, thereby allowing water release and drainage(9).

Bruce and others reported the following negative results with an artificial freezing and thawing process(265): (1) fine solids, that were produced, blinded vacuum filter media; (2) centrifugal dewatering was impractical because the fine solids were discharged with the centrate; and (3) digestion of activated sludge before freezing did not improve its response to freezing and subsequent dewatering.

Clements and co-workers investigated freezing as a sludge conditioning technique prior to vacuum filtration, and obtained a number of positive results from laboratory, pilot plant, and small-scale plant tests, as follows(267): (1) Freezing was an effective sludge conditioning process for all types of sludges. (2) The use of flocculents with freezing was helpful but not necessary. (3) Slow and complete freezing of the total sludge was required for good results (cooling without freezing produced no dewatering improvement). (4) The length of time that sludge was kept frozen before dewatering was not important. (5) The method of thawing was not critical, but it must not be accompanied by vigorous agitation. (6) Freezing accelerated the rate of sludge settling. (7) The supernatant liquid from sludge frozen, thawed and settled approximates the strength of raw sewage.

The use of chemicals, in conjunction with freezing, to condition sludges prior to dewatering was reported to allow unprecedented filtration rates(267). Table 15.1 describes these rates along with cake solids, filtration yields, chemicals used and their dosages. As indicated, the most successful chemicals were aluminum sulphate, chlorine and chlorinated iron sulphate (copperas); they were most effective if added after cooling but before freezing. With vacuum filtration, dewatering occurred in a few seconds and produced a cake with a solids content of 22 to 29 percent.

Table 15.1

| Method of Treatment | Chemical Conc. (ppm) | Time | Filtration Dry Solids Cake (%) | Filtration Dry Solids Rate (Lbs./Sq.Ft./Hr.) |
|---|---|---|---|---|
| (a) | Digested | Sludge | | |
| No chemicals, no freezing | -- | 120 min. | -- | -- |
| No chemicals, freezing | -- | 6 min. | 23.6 | 7 |
| Chlorine, freezing | 250 $Cl_2$ | 3 min. | 22.0 | 14 |
| Chlorinated $FeSO_4$, freezing | 250 Fe | 1.2 min. | 26.9 | 31 |
| Aluminum sulfate, freezing | 100 Al | 3 min. | 26.9 | 9 |
| Aluminum sulfate, freezing | 200 Al | 1 min. | 25.6 | 27 |
| Aluminum sulfate, freezing | 500 Al | 5 sec. | 28.6 | 321 |
| (b) | Activated | Sludge | | |
| No chemicals, no freezing | -- | 10 min. | -- | -- |
| Aluminum sulfate, freezing | 100 Al | 30 sec. | 20.0 | 24 |

The above plus other experiments showed that the filter cakes were porous, friable, and easily removed from the filter media. Filter yields as high as 350 pounds (dry) per square foot per hour were attained with digested sludge when large dosages of alum were used with freezing(267). Activated sludge yields as high as 70 pounds per square foot per hour were possible. A yield of 40 to 50 pounds per square foot per hour was achieved with more realistic chemical dosages of 100 ppm chlorinated copperas or 20 ppm alum(267). Filter yields from freezing without chemicals were good but not spectacular.

Dewatering frozen and thawed sludge on sand drying beds rather than by vacuum filters also greatly increased the rate over that obtained with unfrozen sludge.

Doe and others applied the freezing technique to water plant sludge concentration(459). At the Lancashire, England, water filtration plant, 33,000 gallons per day of a 0.5 percent sludge were concentrated to a gel that occupied an area one-eighth the size of that previously necessary for untreated sludge. The process steps were: (1) gravity thickening with slow picket stirring, concentrating the sludge to 1.9 percent, (2) storage and decanting for at least 16 hours in other tanks which further concentrate the sludge to 2.4 percent; and (3) freezing and thawing to concentrate the sludge to a gel.

The freezing process was independent of freezing temperature and the sludge detention time in the frozen state but, as Clements observed, the process required slow and complete freezing of the sludge(267). Construction cost for the small-scale plant in Lancashire was $178,500 or about $51 per ton (20 year amortization at 4% interest)(459). Operating costs were $57 to $79 per ton, assuming that the feed sludge contained 2.4 percent solids. Doe and co-workers believe that the freezing process offered a secondary advantage: it produced a material that was ideally suited for the recovery of aluminum sulfate.

Freezing operating costs included power, flocculents and refrigerants. It takes 28 B.t.u. to lower the temperature of one pound of sludge from 60°F to 32°F and 142 B.t.u. to freeze a pound of sludge(267). Possibly, the freezing expense may be reduced by using sludge cake thawing for pre-cooling. Clements quoted a total operating cost for freezing of $0.28 (2 shillings) per ton of wet sludge or $5.60 per ton of dry sludge(267). Operating costs of $6.77 to $9.49 per 1,000 gallons have been reported for freeze and thaw cycles, lasting 50 to 120 minutes. Using a 5 percent sludge as a basis, this translates into $32.25 to $45.25 per dry ton(286). This very high operating cost has been the major reason why freezing has not been adopted as a conditioning technique for wastewater sludges. Another problem is the need for dewatering equipment capable of handling the very high production rates possible with the freezing process.

Undoubtedly, artificial freezing can aid sludge dewatering. However, it probably will never be practical, except in isolated cases, unless the economics are improved greatly.

## B. Heat Treatment

In 1951, ten years of full scale operating experience with a heat treatment--sludge conditioning process was completed successfully(275). The unique process, called the "Porteous Process," reduced the water affinity of sludge solids by heating the sludge for short periods(266).

Exposing the sludge to heat and pressure coagulates the solids, breaks down the gel structure, and reduces the hydration and hydrophilic nature of the solids. The liquid portion of the sludge can then be easily separated from the solid by decanting and pressing.

The following data show the relative dewatering rates of sludge conditioned by different agents.

Table 15.2(275)

| Conditioning Agent | Relative Dewatering Rates<br>Primary Sludge | Relative Dewatering Rates<br>Secondary Sludge[1] |
|---|---|---|
| None | 30 | 1 |
| Sulfuric acid[2] | 100 | 2 |
| Aluminum sulfate[3] | 200 | 10 |
| Ferric sulfate[3] | 300 | 15 |
| Ferric chloride[3] | 400 | 20 |
| Lime[3] | 1,000 | 80 |
| Heat treatment[4] | 6,000 | 1,000 |

[1] Mixed humus and activated sludge
[2] At optimum pH value
[3] At optimum dosage
[4] One-half hour at 360°F

As Table 15.2 shows, the dewatering rates of both primary and secondary sludges after heat treatment, exceeded markedly the rates when using chemical conditioners.

As the process was operated at the Halifax, England, sewage treatment plant(275), raw sludge was heated by live steam to temperatures of 290°F to 370°F in pressure vessels. After "cooking" for 1/2 to 3/4 hour at a pressure of 150 psi, the sludge was passed through a heat exchanger, countercurrent to the raw sludge inflow. The sludge was stored and settled overnight and the next day, dewatered in a filter press. Raw sludge solids were 4.9 percent; heated and stored sludge averaged 10.1 percent solids; and the filter press cake averaged 52 percent solids. No chemicals were used. Maximum economy required the use of heat exchange equipment. At Halifax, 75 percent of the heat was recovered with intermittent operations.

In 1951, Lamb gave the total operating cost of the Halifax "Porteous" process as $6.58 per ton of dry solids(275). This cost would be competitive with sludge conditioning and dewatering costs in the U.S.A.

Jepson and Klein conducted numerous laboratory experiments involving the heat treatment of sludge(276). They reported that under high pressures (150 psi), sludges could be thickened from 0.8 to 2.49 percent and from 4.84 to 7.8 percent. The final sludge concentration depended on the steam pressure applied and the treatment detention time. Solid-liquid separation was rapid using the heat treated sludge, but the supernatant contained many solids (up to 36 percent of the original sludge solids) and most of the nitrogen (59 percent of the original nitrogen). The thickened sludge filtered well, but heat treatment inhibited digestion.

Teletzke advocated the use of the Zimpro wet oxidation unit for heat treatment of sludges prior to conventional dewatering(328). Operation of the unit at low pressures (150-300 psig) and temperatures (300-350°F), he stated, can reduce organic sludges to a sterile, nonputrescible end product that can be dewatered without chemical conditioning by vacuum filters, centrifuges, or sand beds. Reliable cost information was not available because heat conditioning prior to mechanical dewatering had not been in full-scale operation at any U.S. sewage treatment plant. The closest approximation was the batch wet-oxidation operation at South Milwaukee, Wisconsin, where digested primary sludge was partially oxidized at relatively low temperatures. Their fuel costs were $11.50 per ton and power costs, $5.25 per ton(328).

Advantages claimed for the Porteous (heat-treatment) process included:

1. No odors.
2. No chemicals required for sludge conditioning.
3. The treated sludge was completely sterilized.
4. Capital and operating costs were similar to those of digesters and sand beds.

A major disadvantage was the newness of the process. Reliable performance and cost data were not available for U.S. operations. Another disadvantage was the high concentration of soluble B.O.D. in the storage-tank decantant and in the filtrate.

Research and development of heat conditioning processes should be encouraged because they offer some very important technical advantages. It appears that costs could be competitive with other methods of sludge treatment. Perhaps heat treatment should be considered wherever solids are incinerated because of the opportunity for optimum heat utilization. It may be particularly useful for conditioning hydrous biologic sludges.

## C. Solvent Extraction

Sludge conditioning by solvent extraction has been tested at the Rockford, Illinois, treatment plant. Described as the "McDonald Process"(269), it involved a series of steps including: (1) dewatering by centrifugation, (2) solvent extraction with carbon tetrachloroethylene, and (3) distillation. The end products were dried oils, fats, and greases. Solvent extraction was an interesting approach to sludge dewatering, but the "McDonald Process" has been described as impractical(269).

## D. Electrical Treatment

Sludge conditioning with electricity has fascinated a number of researchers. Slagle and Roberts treated both sewage and sludge by "electrodialysis"(274). In laboratory experiments, they put sludge in a vessel which was placed in a copper dish containing an equal amount of s[illegible] The copper dish served as the cathode while a carbon anode [illegible] placed in the sludge. Following passage of a direct current, the filterability of the sludge increased, as indicated by the following data:

| | Water removed by vacuum filtration |
|---|---|
| Untreated sludge | 12% |
| Sludge electrodialyzed for 15 min. | 43% |
| Sludge electrodialyzed for 30 min. | 65% |

In their second series of laboratory tests, Slagle and Roberts(274) used three cells: the center cell contained sludge and the outside two contained sewage. A graphite anode was placed in the sludge while iron cathodes were placed in the sewage. Upon the application of a direct current, the cations migrated to the sewage and collected at the cathodes forming metal hydrates which in turn flocculated the sewage. Anions migrating to the sludge caused acid hydrolysis and loss of solids. The sludge again was filterable without chemical conditioning.

Next, Slagle and Roberts(274) tested the process in a pilot plant, where they also used graphite anodes and iron cathodes. Asbestos cloth was used to separate the sewage-sludge compartments. Electrodialysis in this larger system reduced the sludge pH to 3.4, and the sludge could be filtered without the use of chemical conditioners.

The solids in the filter cake (laboratory filtration) varied from 32 to 45 percent. After electrodialysis, the sludge settle rapidly and seemed to be stabilized because there was very little gas after extended detention.

A comparison of electrodialysis conditioning versus chemical conditioning produced the following data using fresh sludge having a 6.56 percent solids concentration(274):

| Chemical Treatment(per ton of dry solids) | Electrodialysis Treatment(per ton of dry solids) |
|---|---|
| 89 lbs. of ferric chloride used | 181 KWH expended |
| 70% filter cake moisture | 59.5% |
| 2,065 lbs. filter cake solids | 1,440 lbs. |
| 4,665 lbs. filter cake water | 2,130 lbs. |
| 6.2 pH | 3.4 |

Conclusions drawn from the results of the above studies were: (1) electrodialysis can condition sludge for filtration and flocculate sewage at the same time; (2) optimum filtration occurred at a pH of 3.4 and required no chemicals; (3) sludge treated by electrodialysis produced a filter cake much drier than chemically treated sludge; (4) as the pH increased the filterability decreased, and conditioning chemicals become necessary; (5) electrodialysis caused a solids loss of 20 percent and an ash loss of 30 to 40 percent; and (6) the most economical current density was about 0.3 amp per square foot of anode surface with a potential drop of 4 volts between the electrodes.

Costs of electrodialysis and chemical sludge conditioning depend, of course, on the price of flocculents and electricity. Typical data indicated that 181 KWH were equivalent to 408 pounds of ferric chloride and 416 pounds of lime. Using a price of $0.01 per KWH, results in much lower conditioning costs for electrodialysis than for chemical treatment(274).

Cooling and co-workers also reported on their experiments with electricity(268). "Electro-osmosis" was the term Cooling used to describe the passing of a current through digested sludge. He concluded that the quantity of water removed from sludge was proportional to the electricity transported. An electro-osmosis permeability of 0.006 gallons per square foot per hour per inch per volt and a constant equal to 0.02 gallons per ampere-hour was used. It was observed that thinner sludges required less current. While electro-osmosis was promising technically, Cooling and his co-workers concluded that the consumption of electricity was too high to be considered practical and that the maintenance problems would result in a very high labor cost. Dried crusts formed on the anodes, reducing the electrical efficiency, and corroded anodes had to be replaced frequently.

Laboratory studies described by Coackley also confirmed the need for greater amounts of energy to remove a given quantity of water as the solids concentration in sludge increased(277). Hicks was able to filter sludge by substituting electrolytic conditioning for chemical treatment(30). He used carbon and iron electrodes. With the application of a direct current, the pH decreased very rapidly to a point where the sludge became filterable.

Beaudoin further dewatered activated sludge filter cake at Chicago by electrical means(273). He also called the process electro-osmosis because water moves through porous sludge after the application of an electric current. High, sludge-drying costs provided the incentive to seek a way to decrease the vacuum filter-cake moisture. Beaudoin concluded that the use of electricity was effective, but it was not economically feasible. He obtained the best results by conditioning the filter cake with 25 volts for 2 minutes.

In summary, it appears that electrical treatment can be substituted for chemical conditioning of a wide variety of liquid sludges, if power economics were the only major consideration. However, the sludge handling and equipment maintenance problems appear to preclude this process until improved techniques are developed.

## E. Ultrasonic Treatment

Conditioning of sewage sludges by ultra or supersonic vibration has been explored in British and European laboratories(270, 277). The available data indicate that this process is not a very successful method of sludge treatment. Ultrasonic vibrations degasify sludge, which is beneficial, but the vibrations also tend to destroy sludge flocs resulting in fine solids that are more difficult to dewater.

## F. Bacteria Treatment

The addition of autotrophic sulfur bacilli to digested sewage sludge has been investigated as a means of sludge conditioning, prior to dewatering. Under aerobic conditions sulfur-oxidizing bacteria stimulate the production of acids. The pH of the sludge is lowered by the sulfuric acid produced, thereby enhancing dewatering processes. Unfortunately no data are available to describe the performance or economics of the process.

## 16. COMPOSTING

General - Composting of wastewater solids, to convert the organic wastes into a humus valuable as a soil conditioner and nutrient source, is a controversial process. It has many supporters attracted by the potential of producing a useful end product from a material considered by most people to be something you should completely eliminate as quickly and cheaply as possible. The conservation principle of returning nutrients to the soil is appealing and, as a result, composting techniques will continue to be discussed if not installed.

It is frequently stated that composting has not caught on in the U.S.A. because we have a tradition of waste that obstructs any interest in reclaiming organic solids. But, attempts to produce and market compost have been made and have failed. Failure is usually due to the inability of the producer to market the compost in competition with other materials such as chemical fertilizers which are relatively cheap, plentiful, easy to apply, and very familiar to the farmers. In comparison, composting has many disadvantages including the fact that the technology is limited, the economics of the process are uncertain, and inorganic fertilizers are often required to be used along with compost.

Definition - Composting has been defined as the "aerobic thermophilic decomposition of organic wastes to a relatively stable humus. Decomposition results from the biological activity of microorganisms which exist in the waste" (418). A good compost could contain to 2 percent nitrogen, about 1 percent phosphoric acid, and many trace elements. Its most valuable features, however, are not its nutrient content, but its moisture retaining and humus forming properties (70).

Many types of microorganisms are involved in converting the complex organic compounds such as carbohydrates and proteins into simpler materials, but the bacteria, actinomycetes, and fungi, predominate. These organisms function in a composting environment that is optimized by copying the natural decomposition process of nature where, with an adequate air supply, the organic solids are biochemically degraded to stable humus and minerals.

History - Composting was widely used in Europe and Asia many centuries ago because there was an agricultural demand for its soil conditioning and nutrient properties. At the beginning of the 20th century, however, compost was replaced by chemical fertilizers that gave better results and were easier to apply (69). Starting about 1930 and accelerating rapidly after World War II, the European interest in composting was revived. Two factors were important in this revival; first, there was a shortage of chemical fertilizers and second, there was a need to do something with the wastewater solids resulting from programs to control water pollution. Composting has become most widely accepted in Holland where at least 25 percent of the organic waste solids have been converted to compost (404).

Use - Compost is generally considered as a material to be used in conjunction with fertilizer, rather than as a replacement for fertilizer unless it is fortified with additional chemical nutrients.

Compost benefits the soil by replenishing the humus, improving the soil structure, and providing useful nutrients and minerals. It is particularly useful on old, depleted soils and soils that are drought-sensitive (69). In horticulture applications, compost has been useful on heavy soils as well as sandy and peat soil. It has been commonly applied to parks and gardens because it increases the soil water absorbing capacity and improves the soil structure.

Parameters - All composting processes attempt to create a suitable environment for thermophilic facultative aerobic microorganisms. If the environmental conditions for biological decomposition are appropriate, a wide variety of organic wastes can be composted. The most important criteria for successful composting are: (1) complete mixing of organic solids, (2) nearly uniform particle size, (3) adequate aeration, (4) proper moisture content, (5) proper temperature and pH, and (6) proper carbon-nitrogen ratio in the raw solids (356, 418).

The smaller the particles, the more rapidly they will decompose; size is controlled by grinding. Air is necessary for aerobic organisms to function in a fast, odor-free manner. Aeration is enhanced by blending wastes to form a porous solids structure in the composting materials. Some composting systems use blowers while others aerate by frequent turning of compost placed in windrows and bins. The solids to be composted must not, of course, contain high concentrations of materials toxic to the decomposing microorganisms.

A proper moisture content is the most important composting criteria (418). Microorganisms need moisture to function but too much moisture can cause the process to become anaerobic and develop the characteristic odor and slow decomposition rate associated with anaerobic processes. Kneiss recommended a maximum moisture content of 50 to 60 percent in the composting mixture (357).

Composting mixtures should have a pH near 7 (neutral) for optimum efficiency. The temperatures vary a great deal but those in the thermophilic range (greater than 110°F) produce a more rapid rate of decomposition than those in the lower mesophilic range. Higher temperatures also cause a more efficient destruction of pathogenic organisms and weed seeds.

An essential requirement of the composting process is control of the ratio of carbon to nitrogen (C/N) in the raw materials. Microorganisms need both carbon and nitrogen, but they must be available in the proper amounts or decomposition will be prolonged. Braun and Kneiss (396, 357) recommended C/N ratios of 25 to 30.

The time required to complete composting varies, depending on the climate, materials composted, the degree of mechanization, whether the process is enclosed, and the desired moisture content of the final product. Composting detention times from a couple of weeks to several months have been reported.

Composting Materials - Many types of wet solids have been successfully used in composting operations. These include sewage sludge, cannery solids, pharmaceutical sludge, and meat packing wastes. Sewage sludge has been frequently used as an additive when composting dry refuse and garbage. It enhances the composting operation because: (1) it serves as a seeding material to encourage biological action, (2) it helps to control the moisture content in the composting mixture, (3) it enhances the value of the compost by contributing nitrogen and other nutrients, and (4) it can be used to control the important C/N ratio. In recent years, the carbon content of refuse has steadily increased in part due to changes in the packaging of consumer products. The use of sewage sludge to increase the nitrogen content of compost is, therefore, useful in promoting an ideal C/N ratio.

Normally, blending sewage sludge with other compost raw materials required prior dewatering of the sludge. If the dewatering step is omitted, the moisture content of the mixture is too high and odors develop. Reducing sludge moisture from 90 to 70 percent by vacuum filtration or centrifugation allows good aerobic composting with garbage at a blended moisture content of 53 percent (351, 357). Gothard recommended a sludge-dry refuse ratio of 0.7 to 1.1 to produce an optimum moisture content of 65 percent (359). Davies recommended a 2:1 refuse-sludge ratio and the use of raw sludge rather than digested because of its higher nitrogen value (360). Black (355) stated that any amount of sludge could be mixed with refuse for composting, provided the sludge was adequately dewatered.

In favorable climates, the composting of digested sludge with sawdust, straw, and wood shavings has been successful (355). Pharmaceutical laboratories have composted their wastewater solids with sawdust and animal manures (378). Mercer described the composting of a mixture of cannery wastes, refuse, and rice hulls (356). It appears that many combinations of waste solids are compatible so long as the critical composting parameters are not ignored. But, wastewater solids from municipalities, food industries, pulp and paper mills, and the pharmaceutical industry are particularly conducive to composting because they have a high organic content which promotes a good C/N ratio.

Processes - Basically, composting consists of three stages: (1) mixing, (2) composting, and (3) maturing. If pieces of metal, glass, and cinders are in the refuse to be composted, sorting and grinding is necessary to remove them. Figures 16.I and 16.II describe two common composting techniques.

The simpler process (Fig. I)(353) is called the rasping or hammermill system. Here the refuse is first sorted by screening and magnetic separation. The remaining particles are then pulverized in a grinder called a rasping machine or a hammermill. Following this, sewage sludge is uniformly blended with the pulverized refuse solids and the mixture is placed in windrows, pits or silos for decomposition and stabilization. The stored material is kept moist and aerated while decomposing.

A more complicated process called the Dano system is described in Figure 16.II (360). After sorting and particle crushing, the material to be composted is conveyed to a large rotating drum called a biostabilizer (69). Composting material is held for 5 days in a slowly rotating drum while air and water are added to optimize the environment. After partial decomposition, the material is ground again and placed in windrows for further decomposition and stabilization.

Both systems produce a material that is non-odorous and easily handled. As a final step, some European plants have used inertial separation processes to improve the value of the finished compost by separating the lighter organic compost from heavier inorganic material.

Wiley and Spillane stated that refuse-sludge mixtures placed in windrows can be effectively decomposed in about 6 weeks, provided that the windrows are thoroughly turned five times during the first 3 weeks of curing (395). He recommended small cross-sectional piles plus frequent turning to prevent oxygen depletion and odor production. Regrinding and moisture adjustment are desirable when turning the compost.

A unique composting system called the "Brikollare Process" has been constructed at Schweinfurt, Germany (351). After pulverization and magnetic separation, sewage sludge and refuse are blended and briquetted under a pressure of 400 psi. The resultant bricks are stored in a curing room and fermented at 160°F. After stabilization, the composted bricks are used for agricultural purposes.

Figure 16.I$^{(353)}$

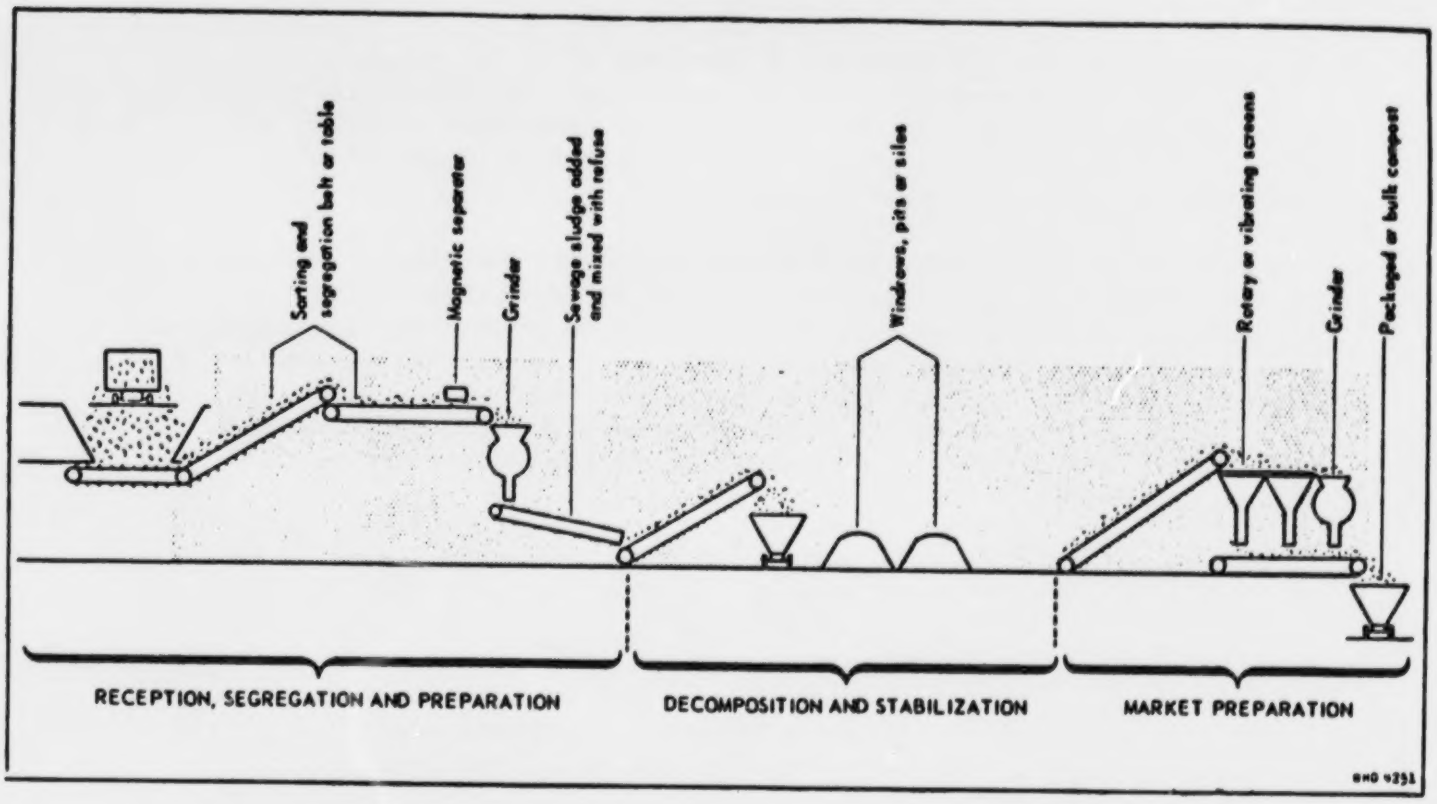
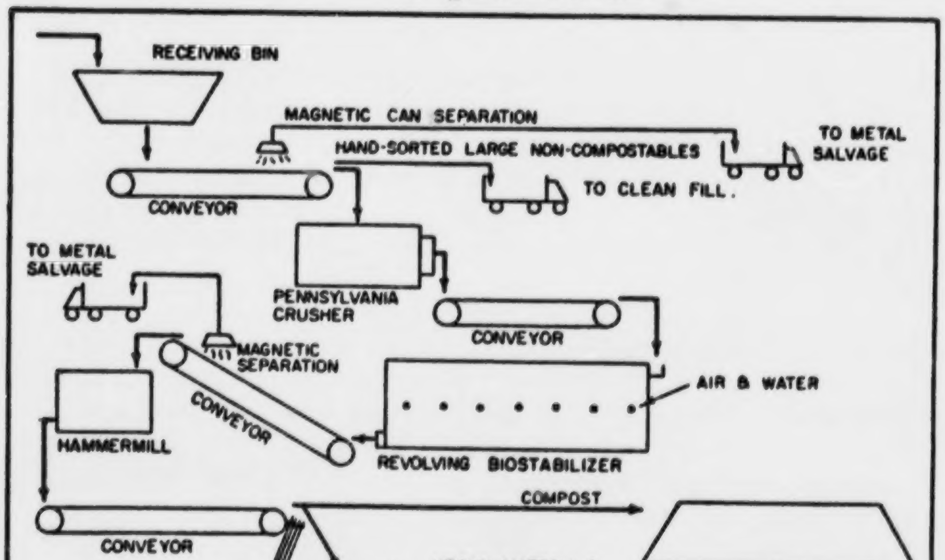

Sorting and segregation belt or table
Magnetic separator
Grinder
Sewage sludge added and mixed with refuse
Windrows, pits or silos
Rotary or vibrating screens
Grinder
Packaged or bulk compost
RECEPTION, SEGREGATION AND PREPARATION
DECOMPOSITION AND STABILIZATION
MARKET PREPARATION

Figure 16.II$^{(360)}$


RECEIVING BIN
MAGNETIC CAN SEPARATION
HAND-SORTED LARGE NON-COMPOSTABLES
TO METAL SALVAGE
TO CLEAN FILL.
CONVEYOR
TO METAL SALVAGE
PENNSYLVANIA CRUSHER
CONVEYOR
MAGNETIC SEPARATION
AIR & WATER
HAMMERMILL
CONVEYOR
REVOLVING BIOSTABILIZER
COMPOST
CONVEYOR
AIR
HEAVY MATERIALS TO CLEAN FILL
WINDROWS

Schematic flow sheet for a Dano composting plant.

(Reprinted by permission Compost Science, Emmaus, Pa.)

Performance - Black reported on a composting study at Chandler, Arizona (355). Sewage sludge and refuse were mixed and composted outdoors in windrows and bins. Periodically the material was reground, wetted, and replaced. Within 30 days, 35 to 40 percent of the volatiles were lost. After composting 43 days, the volatile solids reduction was 50 percent. It was estimated that the same volatile reduction could be accomplished in 9 days with the use of mechanical units having continuous aeration and mixing. Little nuisance was observed from the Chandler tests even when raw trickling filter humus was blended with the refuse. Composting temperatures up to 160°F were reported which should kill pathogenic microorganisms.

Composting in Jersey, the British Isles, was described by Gothard (359). Garbage and refuse were screened, pulverized, and mixed with sewage sludge. The mixture was held for 1 week in fermentation bins and then transferred to outside, but covered, maturing sheds for 6 weeks. Composted mixtures exceeding 10,000 tons per year were used for general agriculture purposes, on golf courses, and for greenhouse soil conditioning.

The Tillo Products Company near San Francisco has been successfully marketing a composted mixture of Bay Area wastes for 15 years. Basic ingredients have included digested sewage sludge, coffee grounds, and rice hulls. On occasion, wood shavings, sawdust, and slaughter-house wastes have also been used. The liquid digested sludge was blended with the food industry wastes and composted for several weeks during which time a temperature of 140°F is generated. At this temperature, it is assumed that weed seeds and pathogenic bacteria are killed. Typical nutrient and trace element concentrations of the Tillo compost were: 1.5% nitrogen, 2% phosphoric acid, 0.25% potash, 3% calcium, and 0.5% magnesium. The Tillo material has a total porosity of 90 percent and a moisture retention factor of 280 percent.

Mercer and others described the composting of wet cannery solids mixed with other materials such as municipal refuse or rice hulls (356). Mixing a maximum of 250 pounds of fruit solids (85% moisture) per 100 pounds of municipal waste achieved an optimum moisture concentration of 70 to 65 percent. The mixture was stored in bins, turned daily for the first week and every other day until composting was essentially complete. At first, a low pH of 4.5 to 5.0 lengthened the required composting period, but the addition of lime corrected this problem. Finished compost had a slight fermentation odor and attracted a few flies but no serious nuisance problems developed. Mercer concluded that air dried compost can be used as the dry component in succeeding blends of fruit waste-compost mixtures.

Subsequent tests by Mercer and co-workers determined that a critical moisture content was 70 percent (406). If the moisture content was kept below this figure by blending wet canning solids with absorbent materials, aerobic composting proceeded satisfactorily. Above 70 percent, the composting proceeded slowly in an odorous anaerobic state. Grinding of the fruit wastes to expose more surface area, and the addition of nitrogen in the form of urea improved the composting process.

Other studies of windrow composting of wet cannery fruit solids with rice hulls as an absorbent material resulted in the following conclusions by Mercer and others representing the National Canner's Association research staff: (1) cannery wastes can be disposed of by composting, (2) mechanized turning of the compost pile is possible, (3) absorbent materials can be used through an entire season because they resist biological degradation, and (4) thermophilic temperatures are developed in the composting process (406).

Composting of 6 to 10 tons per day of pharmaceutical wastes was described by Gabaccia (353, 378). Organic sludges from various fermentation and animal operations are dewatered, mixed, and shredded with sawdust and animal manures. The optimum blend was determined to be:

| | |
|---|---|
| Waste treatment plant sludge | 65% by weight |
| Stable manures | 25% |
| Sawdust | 10% |

After blending, one part of ground rock phosphate was added to each 200 parts of fresh mixture. The material was composted for 5 months in windrows, and then turned over, and restored in cone-shaped piles. After stabilization, the compost was reshredded and applied to lawns as a soil conditioner.

Kneiss reported on the successful use of garbage-sludge compost in Europe as a fertilizer and soil conditioner for orchards and vineyards (357). He also suggested that compost could be used to reclaim barren strip-mined areas.

Economics - Accurate production costs of compost were not available; but they are estimated to be high because of the numerous steps in the process. The steps include: (1) raw material transportation to the compost site, (2) dewatering of wet solids, (3) trash separation, (4) grinding and blending of solids, (5) turning of compost, and (6) regrinding and further processing for commercial sale. It has been estimated the real production costs approximate those for incineration ($35 to $45/ton). Operating costs can, of course, be defrayed by selling the compost, but a market must exist for the material.

Available technical literature contains widely varying compost cost estimates having questionable value because most of them describe overseas operations. The few cost estimates for United States based facilities were as follows:

1. Davies reported that U.S. processing costs in 1956 were less than $3.25 per ton for full time operation and $8.00 per ton for part time operation (exclusive of salvage)(360).
2. In *Compost Science*, a reported 1952 composting cost was $3.00 per ton, if the raw material was delivered free to a 200-300 ton per day facility and if the value of salvaged material was deducted (354).
3. Snell was quoted as stating that the cost of composting in the United States should be $2.00 to $4.00 per ton for a reasonably sized plant (354).
4. Gotaas reported that composting costs were $2.00 to $6.00 per ton (364).

The bases for the above costs are unknown, but they undoubtedly reflected an optimistic attitude and probably included only operating costs. Gothard and Shuval presented more detailed cost for composting analyses in the British Isles and Israel, respectively, but, again, the value is questionable because they describe overseas installations:

Compost Costs - British Isles (359) (1961)
Design capacity = 60 Ton/day
Capital cost = $600,000
Capital cost per ton = $5 per ton at 1961 production rates
Operating costs = $25 per ton (allows for sale of compost)
Total = $30 per ton

The output in 1961 was at 40 percent of design capacity. Operating costs were much lower than the previous incineration operating cost of $75.00 per ton.

Compost Costs - Israeli (363) (1959) - Dano System

| | | | |
|---|---|---|---|
| Design capacity | = | 50 Ton/day | 500 T/day |
| Capital cost | = | $278,000 | $1,220,000 |
| Estimated 1962 production costs | = | $86,500 per year | $642,000 per year |
| or, | | $4.75 per ton | $3.52 per ton |

The actual 1962 production cost was $7.65 per ton of compost produced.

Dependable markets for compost have not been established, at least in the United States. Rodale (391) and Scott (404) said that compost was being sold for $2.00 to $90.00 per ton. The smaller figure was the price for large quantities of raw compost; the larger figure was the price to small specialty markets. Sales to specialty markets (use on gardens and golf courses) require further processing such as the addition of inorganic fertilizer, bagging and other commercial presale preparations. The specialty market is very small when considering the tremendous volumes of wastewater sludges available for composting. Therefore, the farm market with its associated requirement for low compost prices should be developed.

Unfortunately, the true market value of compost has never been determined. Most everyone agrees, however, the economic situation in the United States favors the use of concentrated commercial fertilizers rather than organic soil conditioners (362).

In general, transporting compost from the urban areas providing the raw material to distant farmland would cost more than the value of the fertilizer components.

Summary - In addition to the conservation appeal of "returning nutrients from the city to the country," (351) composting is claimed to offer the following advantages: (1) many types of organic sludges can be composted, (2) it can solve the critical problem of eliminating troublesome sludge, (3) it has an appeal because the sludge can be utilized as opposed to sludge disposal, (4) sludge volumes are reduced and stabilized to a sanitary nuisance-free product, and (5) the end product has real value as a soil conditioner and source of nutrients.

The major disadvantages to composting are high production costs, limited technology, and the uncertainty of a market for the compost. Composting is generally considered to be an untried innovation which discourages support from public officials responsible for municipal waste disposal (404). This fact, together with the lack of a municipal organization for marketing the end product, usually prevents composting from being seriously considered as a practical sludge disposal method.

Less-often-mentioned disadvantages of composting are the possible health hazards due to the inclusion of sewage sludge in composting mixtures and the potential for public nuisance problems involving odors, insects, and rodents. Reeves isolated many strains of Shigella and Salmonella from a composted mixture of air dried sewage sludge and sawdust that had been wetted and turned (366). He cautioned against the use of such compost on vegetable crops. Others have believed, however, that the high temperatures in composting mixtures kill all microorganisms as well as weed seeds in a period of 4 to 6 weeks (356, 401). Cleanliness and prompt handling of the wastes reduces the chances of public nuisance problems.

In 1962 there were more than 100 engineered compost facilities in operation or under construction in various parts of the world but very few were in this country. One survey reported that only three cities in the United States have composted a blend of refuse and sewage sludge (405). The inability to dispose of large quantities of compost at a favorable price was suggested as being the major factor in closing 6 United States composting plants during the period 1962-1964. One factor that has encouraged composting, overseas, is governmental subsidies. The subsidy concept was necessary to attract private investors to assume composting concessions on a profit sharing basis (363).

Composting would be more acceptable if research and development efforts produced improved technology and information on the true value of the end product. Some specific needs are as follows:

1. New information concerning the effects of compost, methods of application, and time of application on soil structure, nutrient release, soil biochemistry, and crop yields (404).

2. New data proving whether or not composting processes disinfected sewage sludge.

3. Improvements in equipment design to sort, grind, and dewater solids and to accelerate the composting process.

4. Realistic capital and operating costs for composting processes.

5. Development of package compost units for use by farmers, small communities and industries generating organic wastes near rural areas.

Some additional cost information describing sewage sludge and refuse composting will probably be generated by the cities of Houston, Texas; Mobile, Alabama; and Johnson City, Tennessee. Houston has been negotiating with various compost companies to process their wastes at a cost to the city of $2.75 to $3.50 per ton. Mobile has a composting plant under construction. A joint TVA-Public Health Service study has been planned for Johnson City (405). The question of whether large amounts of compost can be marketed at a profit should be answered by the Houston and Mobile operations.

The National Canner's Association is working on the fourth phase of a study that will determine compost production costs for the canning industry (406).

When research and development efforts result in lower production costs and determine the real market value of compost, the composting process may become attractive to small rural communities or industries located in areas where a market for the end product is nearby. But, even with system improvements, composting will always be a minor sludge disposal process due to excessive transportation costs of the raw material and finished end product. Its popularity is declining in Europe in favor of mechanical dewatering and incineration. Perhaps there is a message in this trend for the United States.

## 17. DISPOSAL OF DRIED SLUDGE AS A FERTILIZER OR SOIL CONDITIONER

General - Sewage sludge has been used as a fertilizer and soil conditioner for many years. Some industrial sludges such as filter cake from sugar cane mills also have valuable soil conditioning properties. Preservation of organic matter in this fashion has a great appeal to conservationists but the trend is to alternate methods of disposal because of economics. This chapter is concerned with waste sludges that have been air dried on drying beds; mechanically dewatered; or dried by artificial heat. Some systems combine the three drying methods. Detailed information on these dewatering techniques is in other chapters. The use of liquid sludge as a fertilizer or soil conditioner, after preparation by composting or digestion, is also discussed in other chapters.

One outstanding characteristic of sewage and industrial waste sludges is their large difference in fertilizer value. To a great extent these differences are associated with the method of waste treatment, but certainly, the composition of the wastes collected in the sewerage system plays an important role in the ultimate fertilizer value. Usually, the value of sludge as a fertilizer is limited because the nitrogen, phosphoric acid, and potash content is too low. The organic material in sewage sludge does, however, make it a desirable soil conditioner.

Sludge Processing and Composition - The beneficial use of raw sewage sludge on land involves a potential health hazard from pathogenic organisms unless it is artificially heat treated or composted. In addition to the public health aspect, untreated raw primary sewage sludge is not recommended for agricultural use because its physical structure and high grease content have a detrimental effect on the soil structure and the growing plants (383).

Raw waste activated sludge that has been vacuum filtered and heat dried has become a valuable fertilizer and soil conditioner. The largest producers of dried activated sludge are the Milwaukee Sewerage Commission and the Chicago Sanitary District. Because their treatment processes minimize the removal of solids before the activated sludge process, the sludges retain most of the organic solids. The sludges have a higher than normal nitrogen content in part due to the type of industrial waste discharged to the sewerage system.

Digested sludges from all sewage treatment processes are commonly applied to the land after dewatering in mechanical equipment or on sand drying beds. The digestion process, however, decreases the value of the sludge as a fertilizer because nitrogen is lost as is the readily digestible organic matter. Digested sludge primarily consists then of inorganics plus residual organics that soil micro-organisms are slow to degrade (375).

Many chemical analyses have been made of dried sewage sludge. Anderson reported an average nitrogen content for activated sewage sludges of 5.6 percent and an average for digested sludge of 2.6 percent (407). A survey of 10 sewage plants in Ohio showed an average nitrogen content for digested sludge of 1.77 percent and a total phosphoric oxide average of 2.4 percent (407).

Fair and Geyer gave the following approximate fertilizer values for sewage sludge (7):

| | |
|---|---|
| Sludge from plain sedimentation | 0.8 to 5% nitrogen |
| Activated sludge | 3.0 to 10% nitrogen |
| Trickling filter humus | 1.5 to 5% nitrogen |

Digestion will reduce the nitrogen content by 40 to 50 percent. Raw sludge may contain from 1 to 3 percent $P_2O_5$ and 0.1 to 0.3 percent potash.

Table I presents chemical analyses describing treatment plant influent solids as well as raw activated and digested sludge solids (373). It is interesting to note that aeration (activated sludge) causes an increase in the sewage solids nitrogen content. Carbon-nitrogen ratios are of particular interest to agronomists, but they also serve as an indication of organic solids decomposition during different treatment stages (373).

## Table I

## CHEMICAL COMPOSITION OF SEWAGE SLUDGES
(Dry Weight Basis)

| Sewage Treatment Plant | Nitrogen (%) | Carbon (%) | Carbon-Nitrogen Ratio | Phosphoric Oxide (%) | Ash (%) |
|---|---|---|---|---|---|
| Washington, D.C. (Primary Treatment) | | | | | |
| Influent solids: | | | | | |
| Spring | 2.42 | 43.46 | 18.0 | 1.14 | 32.35 |
| Summer | 2.39 | 43.69 | 18.3 | 1.09 | 37.59 |
| Digested Sludge | 2.06 | 28.59 | 13.9 | 1.44 | 52.83 |
| Baltimore, Md. | | | | | |
| Influent solids | 2.23 | 47.09 | 21.1 | 1.29 | 24.16 |
| Activated sludge | 2.36 | 30.37 | 12.9 | 11.01 | 29.70 |
| Humus tank sludge | 5.34 | 37.90 | 7.1 | 3.96 | 32.30 |
| Heat-dried digested sludge | 3.05 | 36.53 | 12.0 | 2.97 | 39.73 |
| Jasper, Indiana | | | | | |
| Influent solids | 2.90 | 42.31 | 14.6 | 1.62 | 32.29 |
| Activated sludge | 3.51 | 23.01 | 6.6 | 2.81 | 52.43 |
| Digested sludge | 5.89 | 22.95 | 3.9 | 3.49 | 36.96 |
| Richmond, Indiana | | | | | |
| Influent solids | 3.80 | 28.21 | 7.4 | 5.19 | 40.94 |
| Activated sludge | 3.02 | 44.04 | 14.6 | 3.64 | 31.37 |
| Digested sludge | 2.24 | 26.36 | 11.8 | 4.34 | 50.09 |
| Chicago, Illinois (Southwest plant) | | | | | |
| Raw sludge | 2.70 | 46.62 | 17.3 | 2.71 | 28.24 |
| Activated sludge | 4.98 | 28.62 | 5.7 | 5.58 | 34.82 |
| Heat-dried sludge | 5.56 | 29.41 | 5.3 | 6.56 | 37.42 |
| Milwaukee, Wisconsin | | | | | |
| Heat-dried sludge | 5.96 | 20.88 | 3.5 | 3.96 | 27.73 |

Because the composition of raw sewage has changed in recent years, Anderson compared certain sludge analyses made over a 20-year period. The change in raw sewage has resulted from industrial wastes, widespread use of phosphate-containing detergents, and the increased use of home garbage grinders. Table 2 lists the nitrogen and phosphorus percentages over 20 years (373). As indicated there has been little change in the nitrogen content of sludge, but the phosphorus content has increased significantly.

Table 2

COMPARISON OF THE NITROGEN AND PHOSPHORUS CONTENT
OF ACTIVATED SLUDGE AND DIGESTED SLUDGE
1931-35 and 1951-55

| Determination (%) | Activated Sludge | | Digested Sludge | |
|---|---|---|---|---|
| | 1931-35 | 1951-55 | 1931-35 | 1951-55 |
| Nitrogen: | | | | |
| Min. | 4.4 | 4.8 | 1.3 | 1.8 |
| Av. | 6.0 | 5.6 | 2.2 | 2.4 |
| Max. | 6.4 | 6.0 | 3.0 | 3.1 |
| Phosphorus ($P_2O_5$) | | | | |
| Min. | 2.0 | 4.0 | 0.8 | 0.9 |
| Av. | 3.2 | 5.7 | 2.1 | 2.7 |
| Max. | 3.8 | 7.4 | 3.8 | 5.0 |

Minor elements in fertilizer are often considered to be important in crop nutrition. Table 3 shows typical values of some minor chemical elements in activated and digested sludge (373). The concentrations vary widely due to differences in industrial waste discharges

## Table 3

## MINOR CHEMICAL ELEMENTS IN ACTIVATED SLUDGE AND DIGESTED SLUDGE

| | Elements (p.p.m.) | | | | |
|---|---|---|---|---|---|
| Sludge | Copper | Zinc | Boron | Manganese | Molybdenum |
| Activated sludge | 385 | 950 | 6 | 65 | 6 |
| Min. | 916 | 2,500 | 33 | 134 | 16 |
| Av. | 1,500 | 3,650 | 74 | 190 | 45 |
| Max. | | | | | |
| Digested sludge | | | | | |
| Min. | 315 | 1,350 | 4 | 30 | 2 |
| Av. | 643 | 2,459 | 9 | 262 | 6 |
| Max. | 1,980 | 3,700 | 15 | 790 | 12 |

Comparing dried sewage sludge on the basis of its humus content, has been suggested by Husmann (408). After a detailed sludge analysis, he totalized those constituents readily available for humus formation. The amount of humus in various sludges was as follows:

| Type of Sludge | Humus (%) |
|---|---|
| Fresh | 33 |
| Digested | 35 |
| Activated | 41 |
| Trickling filter | 47 |

Obviously, primary treatment does not remove all of the humus-like material.

Performance - In general, sewage sludge has proven its value as a fertilizer and soil conditioner. The specific value is obviously influenced by its nitrogen content. In addition, the sludge nitrification rate, or conversion of nitrogen to nitrates, is very important because it indicates the usefulness of sludge to growing plants. Data by Anderson indicated that the nitrification rate for undigested activated sludge is two and one-half times that of digested sludge (373). His data also showed that most of the nitrification accomplished during a growing season takes place within a month after the sludge is added to the soil.

The exact rate of nitrification has been studied by Anderson and other staff members of the U.S. Department of Agriculture (407). They determined that the degree of nitrification of sewage sludge is much less than that of ammonium sulfate. Less than 20 to 25 percent of the sludge nitrogen was converted to the nitrate form in 16 weeks under optimum conditions for nitrification; the conversion was 90 percent for ammonium sulfate. It was concluded that the rate for activated sludge was similar to other natural organic materials. Industrial wastewater sludges had an almost nonexistent nitrification rate.

In addition to their fertilizer value, sludges are useful because they contain necessary trace elements and they improve the soil structure. The total effect increases the soil moisture holding capacity, the organic content, the total nitrogen content, and it improves the soil aggregation (291).

Numerous field and greenhouse evaluations of sewage sludges have been completed. In general, application rates of 10 to 40 tons per acre are recommended (407, 383). Higher rates reduce crop yields due to toxicity from trace elements in the sludge. Sewage sludge has been usually handled in the same manner as farm manure. It is spread and turned under or harrowed, before the crop is planted.

VanKleeck recommended liming of soils receiving dried sewage sludge, that has not been conditioned with lime in a prior vacuum filtration step (383). He listed the following reasons for liming:

1. Lime neutralizes excess acidity and precipitates some metals that may be present in excessive concentrations.

2. It encourages bacterial decomposition of organic solids thereby increasing the effectiveness of sewage sludges.

3. It improves the physical structure of heavy soils and supplies the necessary element calcium.

4. It makes phosphorus more available.

An application of .5 to 1 ton of lime per acre in the fall before the use of fertilizers is suggested.

The use of dried sludge as a fertilizer benefited the following crops: citrus, tobacco, cotton, corn, potatoes, cabbage and various grasses. Yields increased as much as 18 percent above unfertilized crops (407). The increased yields often extended into the third year after a single sludge application (8). Lunt surveyed the use of digested sewage sludge on farmland in Connecticut and arrived at the following conclusions (382):

1. Sandy soils benefited more than loams, as expected.
2. Soils increased 3 to 23 percent in field moisture capacity, non-capillary porosity, and cation exchange capacity.
3. Soil organic matter content increased by 35 to 40 percent.
4. Total nitrogen content increased up to 70 percent.
5. Soil aggregation increased by 25 to 600 percent.

While good results have been achieved from its use alone, the maximum effectiveness of dried sewage sludge usually has been obtained by combining it with inorganic chemical fertilizers.

Marketing Economics - Most treatment plants with heat drying equipment have changed from fertilizer production to sludge incineration or landfilling. The basic reason for abandoning heat drying was the sludge market has not developed to the potential that many predicted for it. Getting a reasonable price for dried sludge has not been possible due to a limited demand. While it seemed reasonable that more value should be attached to soil conditioning with natural organics, the facts are that inroganic chemical fertilizers have effectively and economically increased crop production.

There are some exceptions to the low agricultural market for sewage sludges. For example, Milwaukee, Chicago, and Houston have successfully marketed large quantities of heat dried activated sludge for many years. The price depended on the nitrogen content (5 to 6%); generally it was $12 to $18 per ton. Over 200,000 tons each year were wold by these cities for fertilizing agricultural crops, golf courses, and park land. Using the common values placed on nitrogen, phosphorus and potash as fertilizers; 20¢, 10¢, and 5¢ per pound, respectively, the average activated sludge should be worth $20 per ton and digested primary sludge should be worth $11 per ton (49).

The Milwaukee Sewerage Commission marketed their heat-dried activated sludge under the trade name Milorganite. It was sold to large distributors who in turn marketed the material through jobbers in all 50 States, plus some foreign countries. Home-owners could buy the material in 50 pound bags. An average analysis of Milorganite showed: (1) 6% nitrogen, (2) 4% phosphate, (3) 0.4% potash, (4) 5% moisture, and (5) numerous beneficial trace elements (367). A marketing organization consisting of a sales manager, agronomist, and three office workers were all the personnel required in the sales effort.

The marketing successes at Chicago and Milwaukee were unique in part due to the high nitrogen content of the dried sludge, an objective pursued in the treatment plant design and operation. Other factors were long term contracts, bulk sales, and the effectiveness of the sludge as a fertilizer. The usual situation revealed by surveys of sewage treatment plants across the country was that heat drying of sludge was not economical and,therefore, was replaced by other handling techniques ((66, 323).

A survey in 1955 of 23 cities, 35,000 to 4,500,000 population, indicated that only Schenectady, New York, was satisfied with its sale of dried sludge (66). Schenectady sold 65 pound bags of Orgo for $1.00 (30.80/Ton). At this price much of the operating costs for heat drying were recovered.

Sludge was sold in small quantities (outside of Chicago, Milwaukee, and Houston) at $1.00 to $80.00 per ton. The price that a buyer was willing to pay for sludge depended on several factors such as the method of preparation, type of raw materials in the system, location of the sludge with respect to the point of use, and kinds of crops or vegetation to be fertilized (407).

Many plants found that granulating the dried sludge make it more appealing to potential users. Most cities that dried sludge on sand beds, gave the material to anyone willing to haul it away. Even at no charge, this had the advantage of ultimate disposal because the sludge was moved off the plant property. Not even the ash from incineration processes was left for disposal.

In addition to competing with chemical fertilizers, sewage sludges have to compete with other organic wastes. Table 4 compares the chemical composition of some wastes with sewage sludges (369).

## Table 4

## CHEMICAL COMPOSITION OF VARIOUS FERTILIZERS (%)

| Fertilizer | Nitrogen | Phosphorus as $P_2O_5$ | Potassium as $K_2O$ |
|---|---|---|---|
| Cottonseed Meal | 7.0 | 2.5 | 1.5 |
| Chicken Manure | 4.1 | 3.7 | 2.3 |
| Average Farm Manure | 1.2 | 1.2 | 1.2 |
| Average Activated Sludge | 5.6 | .4 | .4 |
| Average Digested Sludge | 2.0 | .2 | .2 |
| San Diego Digested Sludge | 2.7 | .8 | .8 |

Sewage sludge competed most often with farmyard manure and certain seed meals because their effectiveness as fertilizers was similar. Table 5 shows the 1958 prices of some nitrogen in the form of organic sludges and inorganic fertilizers (367). Farmyard manure is relatively inexpensive and often close to the point of use, but it is in short supply.

## Table 5

## WHOLESALE PRICES OF NITROGEN AT POINTS OF ORIGIN

| Material | Approximate Nitrogen Content (%) | Price per Pound (cents) |
|---|---|---|
| Milwaukee, Wisconsin, sludge | 6 | 35 |
| Chicago, Illinois, sludge | 5-6 | 25 |
| Baltimore, Maryland, Sludge | 3 | 10 |
| Washington, D.C., sludge | 2 | Free |
| Lancaster, Pennsylvania, stockyard manure | 1.5 | 10 |
| Cottonseed meal | 6.5 | 48 |
| Urea-form | 38 | 36 |
| Anhydrous ammonia | 82 | 5 |
| Ammonium sulfate, synthetic | 21 | 9 |

Summary - Many tons of dried sewage sludge have been sold each year as a fertilizer or soil conditioner, but the sales have been generally by three large activated sludge plants or small towns in rural areas. Large industrial towns would generally have a difficult time marketing sludge because of the quantities handled and the distant location of the markets. Other problems associated with the agricultural use of sludge are: (1) occasional odors when the sludge is wetted, (2) excessive labor to remove it from drying beds, (3) necessity for grinding in most cases, (4) difficulty in proper spreading, and (5) possible disease transmission (14).

Odors can be reduced by storing the sludge for a few months before spreading and by proper treatment plant operation. There have been no reported cases of disease transmitted by the use of heat-dried raw sludge or dewatered digested sludge, but the concern about disease transmission is legitimate, therefore, the use of dried sludge is regulated by various health departments. Regulations promulgated by the Connecticut Department of Health are typical of those throughout the country (383):

1. Heat-dried sludge is safe for use under all conditions because heat destroys microorganisms.
2. Air-dried or mechanically dewatered digested sludge may be used on lawns, shrubs, flowers, and beneath trees. Storage for several months before spreading is recommended. The same sludge may be used on vegetable plots provided that the edible portion of the crops grow above ground or the crops are cooked before eating.
3. When the above sludge is used on soil where vegetables are grown in contact with the soil and eaten raw, the sludge should be applied the previous fall and plowed under before the crop is planted.
4. The public should be warned to avoid handling sludge with bare hands.

The two most important advantages of using dried waste organic sludges for agriculture are: (1) it returns a natural resource to the land, and (2) it represents ultimate disposal of solids. Sewage sludge is generally recognized as a material that can increase soil fertility. In the future, as intensive farming continues, more attention will have to be given to returning essential minerals and organics to the soil.

After reviewing the advantages and disadvantages of drying sludge agricultural use, few consulting engineers today seriously consider the installation of heat drying equipment. Heat drying is the most expensive of all conventional sludge processing techniques. This fact, plus a low market price and a limited demand, makes investment in heat drying equipment a risky business.

Sludge is a liability at all waste treatment plants, even Chicago and Milwaukee lose many dollars in the sale of their heat-dried activated sludge. But sludge from small treatment plants naturally dried on sand beds will continue to be used as a soil conditioner because the volume is small and the material is usually given away. At small plants this method of sludge disposal is simpler and less expensive than most other accepted techniques. It will continue to be successful as long as sludge disposal has top priority over sludge sales.

Improving the economics of dewatering and heat drying would increase the use of sludge, as would fortifying the sludge with nitrates, potash and phosphates. Obviously, fortifying sludge with inorganic fertilizers involves higher costs, a definite disadvantage.

New research is needed to determine the soil conditioning value of dried organic sludges. Many studies have been made but their scope was too limited. A broad scientific study could probably prove that sludges are of inestimable values to agricultural businesses.

Effective public relations campaigns to promote dried sludge are also needed. For example, most cities with dried sludge have made no major effort to sell nearby farmers on the value of the sludge as a fertilizer and solid conditioner.

## 18. NON-FERTILIZER BY-PRODUCT RECOVERY

General - Using water and wastewater solids rather than disposing of them, is certainly an applaudable concept. But, waste utilization is not necessarily profitable, more likely it is a means of reducing sludge disposal costs.

Factors that should be considered when evaluating by-product recovery include: (1) relative costs of sludge disposal and by-product recovery, (2) market value of by-product and marketing problems that may be encountered, and (3) research and development problems that may be involved with by-product systems.

The marketplace determines the by-product specifications. These could be very rigid limitations involving product purity and concentration. The waste sludge processing cost to meet rigid specifications could, of course, be very high. Most industries who have investigated waste by-product recovery, concluded that it is much easier to sell or give the material to a refiner who assumes responsibility for its ultimate disposition.

### Reported By-Product Recovery Methods and Materials:

Sewage Sludge-Vitamin $B_{12}$, Grease and Protein - The recovery of vitamin $B_{12}$, particularly from sewage sludge, has been frequently discussed in the literature. Vitamin $B_{12}$ is a valuable supplement to animal feeds.

Two factors influence the $B_{12}$ concentration in sewage sludges: (1) nature of the incoming solids (whether food industries contribute a significant portion of the total waste solids), and (2) manner in which the sewage is treated. Does it receive secondary treatment? Are the solids digested anaerobically? Vitamin $B_{12}$ has been successfully recovered from dried, undigested activated sludge in pilot plant facilities. Extensive studies at Milwaukee determined that $B_{12}$ is derived in part from raw sewage and partly from biological synthesis in the activated sludge aeration tanks (412). The $B_{12}$ production process at Milwaukee started with the dried waste activated sludge (Milorganite). Commercial heat drying of the sludge caused a 60 to 75 percent loss of vitamin $B_{12}$ from the starting concentration of 3.5 to 4 mg/kg of sludge (412). The Milorganite was subjected to multiple-effect washing, followed by a continuous draw off of concentrated extracted liquor (424). The liquor was concentrated to a syrup in vacuum evaporators and then spray dried. Milorganite, with $B_{12}$ extracted, can be redried and sold with no decrease in value. The pilot plant operation indicated that 308 pounds of pure vitamin $B_{12}$ could be produced each year from Milwaukee's 70,000 ton per year sludge supply.

In a cooperative study by the University of Wisconsin and City of Milwaukee, dried activated sludge was fed to hogs as a protein source (424). Leary summarized that while the sludge contained 40 percent protein, it could not be used as a hog feed. Milorganite was also fed to rats and chicks as a vitamin supplement; its benefits were comparable to that of yeast.

The Metropolitan Sanitary District of Greater Chicago supported research studies at the University of Illinois to determine the value of heat dried activated sludge as an additive to animal feeds (66, 423). They considered that activated sludge was a good source of vitamin $B_{12}$ and essential amino acids. After feeding studies with chicks, pigs, lambs and steers, Hurwitz concluded that sludge was a successful beneficial additive if limited to a small percentage of the total animal feed. For example, activated sludge levels of 0.5 to 2.0 percent were a satisfactory source of vitamin $B_{12}$ for pigs and chickens (66). The studies detected no pathological symptoms in the pig or chicken tissues.

Rudolfs and Cleary described the "Miles Acid Process" for extracting grease from raw sewage solids (35). Sewage was mixed with sulfurous acid which precipitated the solids and killed the microorganisms. After investigations in Boston and New Haven, it was concluded that the process could be worthwhile if the sewage had a very high grease content and low alkalinity.

Food Industry Sludge - The food industry has been very interested in using waste products to increase profits and reduce air and water pollution. Food waste sludges have the disadvantages, however, of high moisture and fiber content plus a lack of stability which complicates storage of the seasonal production.

1. Citrus. The use of waste activated sludge from the citrus industry has been evaluated as a source of vitamin B and protein. Vitamins of the B group contained in this sludge include: thiamin, $B_{12}$, riboflavin and niacin (409). After the sludge is filtered, dried and pulverized, it may be used as an animal feed supplement.

   Citrus pulp has been extensively used by itself as a cattle feed. After dehydration the pulp has been sold for \$30 to \$45 per ton (416, 430). Without dehydration, citrus wastes have been sold as cattle feed for \$4 per ton or converted to molasses and sold for \$40 per ton. Pectin is also made from citrus wastes and used in jams and jellies.

2. Winery. During World War II tartaric acid and tartrate salts were manufactured from winery wastes. But today, the process is not considered economical (428). The pomace portion of the waste has been used as a vineyard soil conditioner or sometimes dehydrated and sold as a cattle feed supplement and plant mulch.

3. Canning. The disposal of wet solids from the canning industry has been a major problem. In California, some canning wastes have been barged to sea at a relatively high cost. Composting has been investigated and seemed promising. A small portion of the total canning waste has been dehydrated and used for animal feed (417). About 15 tons of bulk tomatoes **are** required to make one ton of dehydrated feed. The cost of producing this feed was reported to be $47 to $53 per ton of feed (capital and operating costs) (430). As in most waste disposal operations there was a net cost to the industry generating the waste, but by-product utilization can be cheaper than other methods of disposal.

4. Meat. Grease and fats recovered in meat processing are valuable raw materials for soaps, gelatin and glue. By-product recovery techniques have been easy to justify in this industry because of the large U.S. and overseas market for high quality grease and fat. A price of $.045 per pound for the recovered material was quoted in 1963 (416). Semi-solid meat processing wastes were sold at $.04 per pound for use as animal feed. The Carver-Greenfield dehydration system installed at Hershey Estates, Pennsylvania, can recover greases from combined sewage and industrial wastes. The process includes sludge grinding, fluidizing with oil, three-stage evaporation, centrifuging of solids, and solid pressing.

5. Brewery and Distilling. Wastes from brewery and distillery fermentation have been converted to valuable by-products for many years. The two major by-products are high priced animal feed and Brewer's yeast.

   In the 5-year period from 1945 to 1950, the nation's distillers sold nearly $116 million worth of by-product feed (427). Spent grain mash used to be a serious water pollution problem but now the distilling industry has recovered more than 90 percent of its fermentation residues for sale as animal feed (415). The residue has a high concentration of vitamins and protein that, when mixed with other materials, makes a premium cattle feed.

The spent grain drying process usually involves: (1) screening to an 83 percent moisture content, (2) pressing to 65 percent moisture, and (3) drying in a rotary dryer to 8 percent moisture (427).

Residual yeast from brewery and distillery fermentation is also valuable as an animal feed because it contains vitamin B complex, protein, and essential minerals. Lipsett recorded the breakdown as: (1) 46 percent protein, (2) 37 percent carbohydrate, (3) 8 percent minerals, and (4) 1 percent fat (427). In 1946 the dried yeast sold for $.08 to $.20 per pound. Eighty-five to 90 percent of the drum-dried yeast market has been for poultry, livestock, and specialty feeds. Some has been used in dog food (426). Drying stabilizes the residual yeast by deactivating the enzymes. It also improves the yeast's digestability.

Singruen believes that a brewery must have one million pounds of yeast solids per year to justify drying equipment. This quantity requires a brewery capacity equal to two million barrels per year. He suggested that residual yeast could be collected from several breweries and dried at a central point.

6. Potato. Douglass observed that potato processing pulp is a good cattle feed (420). Because the solids are hydrophilic, dewatering and drying the pulp is difficult. The 5 to 13 percent solids pulp can be dewatered to 30 to 35 percent solids by pressure filtration after conditioning the pulp with lime.

Paper Industry - The paper industry has investigated the possibility of using deinking wastewater sludges in the following applications: (1) lightweight aggregate for building blocks, (2) filler for asphalt tile and liquid emulsions, (3) filler for fiberboard and other lined boards, and (4) filler for paper, rubber, and other manufacturing materials. Deinking sludge solids contain 50 to 75 percent clay, making them particularly useful in the above applications (421).

Bottenfield and Burbank described the recovery of lime from causticizing operations in the kraft wood pulping process (413). Lime muds from a kraft process mill and the mill water softening plant were first dewatered on vacuum filters to a 55 percent solids concentration. This concentrated slurry was then calcined in a natural gas fired kiln at a temperature of 1600°F. The kiln output of 160 tons of lime per day reflected a lime recovery rate of 97 percent. This recovery of a valuable raw material, in addition to solving a solids disposal problem, saved the pulp mill $1,600 per day. Other lime reclamation data are included in the chapter on Water Plant Sludge Disposal.

Other Industrial Sludge By-Product Techniques:

1. Chemical and Petroleum. Waste tars, "spent" catalysts, and other materials from petrochemical processing have often been used by reclamation companies to recover metal from the tars and catalyst complexes (16). Giving away the waste tars eliminates the necessity of on-site disposal by incineration or some other relatively expensive procedure.

   Carbide lime slurries, an acetylene process by-product, and aluminum chloride are two other "waste" materials from the chemical industry that can be salvaged. They are useful as sludge conditioning agents prior to dewatering.

2. Mineral Industry - The refining of alumina from bauxite ore produces a mud in the filtering operations that is a source of alumina oxide. Alumina oxide is recovered by remixing the refuse mud with chemicals and sintering it at 1800°F in rotary kilns (414).

Other by-product possibilities mentioned in the literature concern fish processing, beet sugar processing and metal finishing.

Summary - By-product recovery of useful materials from municipal and industrial sludges should be given serious consideration because it may: (1) eliminate or reduce a water pollution problem, (2) save raw materials cost by reuse, (3) reduce the cost of operation, and (4) cause greater stability in process operations. But, recovery processes involve risks and, therefore, careful planning is required for their success. Some criteria are: (1) the process must be inexpensive in order for the by-product to compete with other materials, (2) if producing animal feed the material must be free of substances harmful to animals and it must be easily digested, and (3) the materials should have a narrow concentration range of valuable constituents (425).

Many industrial sludges often contain too great a variety of materials which make by-product recovery uneconomical. However, the success of the brewery and distilling industry certainly indicates by-product recovery is possible and economical in some situations. Because incineration as a sludge disposal technique is becoming so popular, perhaps particular attention should be directed at finding a beneficial use for the incinerator ash.

## 19. SLUDGE COMBUSTION

Introduction - Incineration of municipal and industrial refuse has been a standard practice for many years. The combustion of semi-solid sewage and industrial waste sludge is a relatively recent innovation. Dearborn, Michigan, installed the first full-scale sewage sludge incinerator in 1935 (287). Sludge combustion is becoming increasingly popular as land areas for sand beds, lagoons, and landfills become more difficult to find and more expensive. The land situation is magnified by ever-increasing volumes of sludge to dispose of and by the encroachment of urban neighborhoods on land disposal areas. There is no doubt that sludge combustion will in the future be adopted by more and more industries and cities because it represents a sanitary method for ultimate sludge disposal (at least for the organic portion of the sludge) in a relatively small land area. For many industries and cities, incineration will provide the only practical answer to sludge disposal.

Incineration is practiced for two basic purposes, volume reduction and solids sterilization. Fulfilling these purposes is expensive and it may cause an air pollution problem. But the economics of combustion appear more favorable each year as the alternative sludge disposal methods become more expensive. Air pollution problems can be solved by proper equipment design and operation.

Sludge Characteristics - Russell says the following sludge parameters are most important in the incineration process: (1) moisture, (2) volatiles, (3) inerts, and (4) calorific value (65d). Of the above, moisture is the principal characteristic, over which the treatment plant operator has some control. Moisture is generally reduced by mechanical sludge-dewatering techniques before incineration. It is important because of the thermal load it imposes on the incineration process with consequent effects on self-sustained sludge combustion.

Volatile and inert materials affect the calorie or B.t.u. value of the sludge. They are, to some extent, controlled by other treatment processes such as degritting, mechanical dewatering, and sludge digestion. Almost all of the combustibles are present in the sludge as volatiles, much of it in the form of grease. The volatile percentage and, therefore, the heat value can vary widely, so incineration equipment must be designed to handle a broad range of values.

Table 19.1 by Owen describes the most important incineration parameters for many of the solids generated at a sewage treatment plant (321).

Table 19.1

| Material | Combustibles (%) | Ash (%) | B.t.u./ Pound |
|---|---|---|---|
| Grease and scum | 88.5 | 11.5 | 16,750 |
| Raw sewage solids | 74.0 | 26.0 | 10,285 |
| Fine screenings | 86.4 | 13.6 | 8,990 |
| Ground garbage | 84.8 | 15.2 | 8,245 |
| Digested sewage solids and ground garbage | 49.6 | 50.4 | 8,020 |
| Digested sludge | 59.6 | 40.4 | 5,290 |
| Grit | 33.2 | 69.8 | 4,000 |

As a general rule, the thermal value of sewage sludge is considered to be 10,000 B.t.u. per pound of volatile solids. If the ultimate analysis is known, Owen claimed that the heat value can be precisely computed by using the DuLong formula (321):

$$Q = 14{,}600\ C + 62{,}000\ (H - \frac{O}{8})$$

where Q = B.t.u./lb.
C = % carbon
H = % hydrogen
O = % oxygen

Theory - Incineration processes involve two steps: (1) drying and (2) combustion. In addition to fuel and air; time, temperature, and turbulence are necessary for a complete reaction. The drying step should not be confused with preliminary dewatering; this dewatering, usually by mechanical means, precedes the incineration process in most systems. A sludge, having a moisture content of about 75 percent is delivered to the most common types of incinerators. Since the typical sludge contains about 3 pounds of water for each pound of dry solids, the heat required to evaporate the water nearly balances the heat available from combustion of the dry solids (65d).

Drying and combustion may be done in separate pieces of equipment or successively in the same unit. Manufacturers have developed widely varying types of sludge drying and combustion equipment. These include traveling-grate furnaces, rotary-kiln-type furnaces, fluidized-bed units, wet-oxidation units, atomized spray units, multiple hearth furnaces, and flash-drying units.

The drying and combustion process consists of the following phases: (1) raising the temperature of the feed sludge to 212°F, (2) evaporating water from the sludge, (3) increasing the water vapor and air temperature of the gas, and (4) increasing the temperature of the dried sludge volatiles to the ignition point (65d).

Practical operation of an incinerator requires that air in excess of theoretical requirements must be supplied for complete combustion of the fuel. The introduction of excess air has the effect of reducing the burning temperature and increasing the heat losses from the furnace. For this reason, a closely controlled minimum excess air flow is desirable for maximum thermal economy. The amount of excess air required varies with the type of burning equipment, the nature of the sludge to be burned, and the disposition of the stack gases.

Fuel (sludge) burned in a furnace emits heat; some is absorbed by the furnace and is lost by radiation, a larger portion is lost with the stack gases, and a smaller portion is lost with the ash. The difference between the heat generated and the heat lost is available for heating the incoming sludge and air. Self-sustained combustion is often possible with dewatered raw sludges once the burning of auxiliary fuel raises incinerator temperatures to the ignition point.

The primary end products of combustion are considered to be water, sulfur dioxide, carbon dioxide, and inert ash.

## A. Multiple Hearth

General - The multiple hearth furnace is the most popular sewage sludge incinerator in use today. There are about 115 of these units installed for sewage sludge combustion (333). Incineration in multiple hearth units is particularly popular in large cities where alternative final sludge disposal techniques are inconvenient or too expensive.

Dewatering the sewage sludge feed, usually by vacuum filtration, is almost always a standard operating procedure. Either raw or digested sludge can be incinerated but digestion causes a loss of combustible organic matter, which reduces the heat value of the sludge. As a result, auto-combustion (or burning without auxiliary fuel except for start-ups) is usually not possible as it is when burning raw sludges having a higher volatile content.

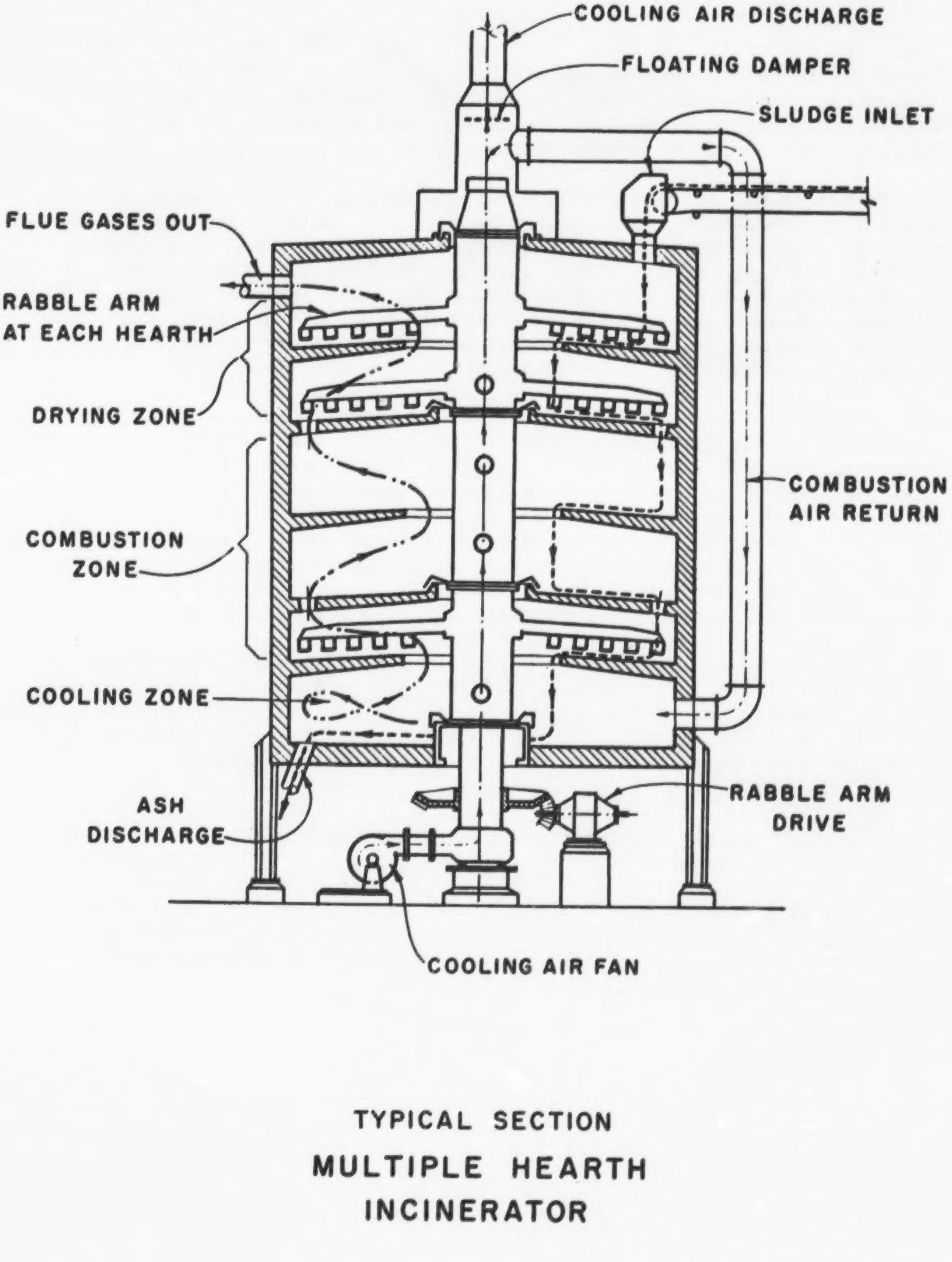
Multiple hearth units are popular because they are simple, durable, and have the flexibility of burning a wide variety of materials even with fluctuations in the feed rate.

Design and Operation - The multiple hearth furnace consists of a circular steel shell surrounding a number of solid refractory hearths and a central rotating shaft to which rabble arms are attached. Since the operating capacity of these furnaces is related to the total area of the enclosed hearths, they are designed with various diameters and a varying number of hearths, usually between four and eleven (321). Each hearth will have openings that allow the sludge to be dropped to the next lower hearth.

The central shaft and rabble arms are cooled by air supplied in regulated quantity and pressure from a blower discharging air into a housing at the bottom of the shaft. An annular space between the inner "cold air tube" and the outer wall of the shaft exposed to furnace heat serves as a conduit for hot air. Rabbling is very important to combustion because it breaks up the large sludge particles, thereby exposing more surface area to the hot furnace gases that induce rapid and complete combustion. A typical multiple hearth furnace is described in Figure 19.1.

Owen recognized four distinct zones in the multiple hearth furnace when combustion of wet sludge is carried out to practical completion (321). Partially dewatered sludge is continuously fed to the upper hearths which form a drying and cooling zone. Here, vaporization of some free moisture occurs as well as cooling of exhaust gases, all by transfer of heat from the hot gases to the sludge.

Figure 19.I


COOLING AIR DISCHARGE
FLOATING DAMPER
SLUDGE INLET
FLUE GASES OUT
RABBLE ARM AT EACH HEARTH
DRYING ZONE
COMBUSTION AIR RETURN
COMBUSTION ZONE
COOLING ZONE
RABBLE ARM DRIVE
ASH DISCHARGE
COOLING AIR FAN

TYPICAL SECTION

MULTIPLE HEARTH INCINERATOR

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Intermediate hearths form a high temperature burning zone, or combustion chamber zone, where all volatile gases and solids are burned. Combustion of most of the total fixed carbon takes place on the lowest hearth of the combustion zone.

The bottom hearth of the furnace functions as a cooling and air-preheating zone where ash is cooled by giving up heat to the shaft cooling air which is returned to the furnace in this zone. Incinerator temperatures range from 1,000°F on the top hearths to 1,600-1,800°F on the middle hearths to 600°F at the bottom. In many incinerators the waste gases from combustion are heated to 1,250°F or higher to guard against odor nuisance. Exhaust gases leaving the incinerator at the top are scrubbed in a wet scrubber to remove fly ash.

Some incinerator specifications have been written to require deodorization of gases leaving the furnace by increasing the temperature to about 1,500°F. The simplest method of doing this involves conducting the gases to a chamber where the temperature is raised by burning auxiliary fuel in direct contact with the gases before venting to the atmosphere. This method is expensive due to the fuel cost. A heat recovery device can improve the economy of high temperature deodorization but this requires expensive deodorization and combustion air preheating equipment.

The ash discharged from multiple hearth furnaces is essentially free of all organic solids; therefore, nuisance problems are not expected. Ash is generally transported from a furnace by one of three methods: (1) hydraulic, (2) mechanical, and (3) pneumatic. The hydraulic system is preferable if land for lagooning is available nearby because this method is simple and adaptable.

Hydraulic systems can handle most types of ash regardless of temperature and particle size.

When land availability prevents the use of lagoons, ash is stored dry and periodically hauled away to convenient fill areas. Mechanical conveyors are preferable to pneumatic systems for transporting ash from the furnace to storage bins (302).

Performance and Economics - Incineration is generally considered to be more expensive than other sludge disposal processes. Bartlett-Snow-Pacific, Inc., showed the following approximate costs for sewage sludge incineration at cities of varying populations (319):

| Population | System Cost | Annual Operating Cost |
|---|---|---|
| 6,000 | $ 90,000 | $ 2,300 |
| 10,000 | 100,000 | 3,500 |
| 25,000 | 135,000 | 5,700 |
| 50,000 | 150,000 | 8,800 |
| 100,000 | 185,000 | 17,500 |
| 250,000 | 375,000 | 40,000 |

The figures include vacuum filtration equipment, chemicals, power, fuel, and maintenance.

Assuming that the incinerator handles 0.15 pound of dry solids per person, the annual operating cost on a per ton basis would be:

| Population | Annual Operating Cost ($ per Ton) |
|---|---|
| 6,000 | $13.95 |
| 10,000 | $12.80 |
| 25,000 | $ 8.33 |
| 50,000 | $ 6.42 |
| 100,000 | $ 6.38 |
| 250,000 | $ 5.84 |

The above costs appear to be a little low, particularly for digested sludge filtration and incineration.

MacLaren estimated that the capital cost of incinerators, assuming the capacity is divided between two or more units, was $5 to $10 per ton of dry solids based on a 30-year amortization at 5% interest (53). He estimated that operating costs were $4 to $7 per ton. The total annual cost would, therefore, be $9 to $17 per ton of dry solids.

Quirk made a precise study of sewage sludge incineration costs using, as a model, digested sludge from a city of about 100,000 contributing 2,530 tons of solids per year. In summary, his incineration cost data show (65e):

Capital Cost (includes vacuum filtration but not external ash disposal facilities)

| | |
|---|---|
| 1. Incineration w/o deodorization | $11.75/Ton |
| 2. Incineration w/ deodorization | $12.07/Ton |

| Operating Cost | |
|---|---|
| 1. Vacuum filtration | $7.91/Ton |
| 2. Incineration w/o deodorization | $6.36/Ton |
| 3. Incineration w/ deodorization | $9.50/Ton |

| Total Annual Cost of Solids Disposal | |
|---|---|
| 1. Without deodorization | $26.02/Ton |
| 2. With deodorization | $29.48/Ton |

Variables in the cost of sludge incineration have been due generally to the following parameters(310):

1. Size and design of treatment plant.
2. Nature of waste sludge.
3. Amount and type of chemicals used for sludge conditioning prior to mechanical dewatering.
4. Efficiency of mechanical dewatering.
5. Site conditions and degree of nuisance control.
6. Skill of operating labor, their productivity, and operating schedule.
7. Management competence.
8. Record keeping procedures.
9. Extent of standby facilities built in.
10. Cost of utilities (fuel, water, power).

The literature reported wide variations in operating costs. Part of this variation was due to the variation in supplemental fuel requirements. A survey of numerous incineration facilities showed a variation from less than 1 percent to 35 percent of the heat value supplied by the sludge cake itself(296). It should be remembered that all installations use some fuel during start-up. Schroepfer reported, as expected, a wide difference between the fuel required for raw sludge incineration and for digested sludge incineration(296). Raw sludge units required an average of 1.75 percent additional heat in the form of fuel while digested sludge required 17.9 percent, or ten times as much. This variation could mean a difference in operating costs of $1.06 per ton.

The difference in heat value between polymer conditioned sludges and those conditioned with inorganic flocculents is significant. A typical comparison is as reported below:

Ferric Chloride and Lime Conditioned Sludge

| | Total Solids | Volatile Solids |
|---|---|---|
| Assume | 100 lbs. | 70 lbs. |
| 5% $FeCl_3$ adds | 3.3 lbs. | 0 lbs. |
| 15% lime adds | 20.0 lbs. | 0 lbs. |
| | 123.3 lbs. | 70 lbs. |

Therefore, the true percentage of volatiles = $\frac{7.0}{123.3}$ or 57%

Assume average filter cake solids of 25% and a heat value per pound of volatile solids of 10,000 B.t.u.

The heat value of 1 pound of wet cake = .25 x .57 x 10,000
= 1,425 B.t.u./lb.

But, the calcining effect on ferric chloride and lime requires heat:

(1) lime = 388 B.t.u./lb., and
(2) ferric chloride = 63 B.t.u./lb.
for a total of 451 B.t.u./lb.

So, the actual heat value is 1,425 - 451 or 974 B.t.u./lb.

Organic Polymer Conditioned Sludge

The percentage of volatiles remains at approximately 70%.

The heat value of 1 pound of wet cake = .25 x .70 x 10,000
= 1,750 B.t.u./lb.

There is no heat consumed by calcining.

Therefore, the difference in heat value between these two sludges is 1,750 - 974 or 776 B.t.u./lb.

which equals 1,552,000 B.t.u./ton of wet solids
or 6,000,000 B.t.u./ton of dry solids

A general review of incineration costs showed the following:

| | Average ($) per Ton | Range |
|---|---|---|
| 1. Total cost (dewatering + | $30 | $10-$50 |
| incineration, etc.) | $20 | $ 8-$40 |

Some interesting modifications of conventional multiple hearth incineration have been reported in the literature. For example, Piqua and Ashland, Ohio, have incinerated raw unfiltered sewage sludge for over 15 years(28). The furnaces incorporated no special features for handling the liquid sludge other than the sludge feeding arrangement and the addition of extra fuel burners. At Piqua, the average concentration of sludge burned was 14.2 percent (the range was 8 to 17 percent). As would be expected, the incineration of liquid sludge resulted in excessive supplemental fuel costs; the average requirement was 88 gallons per ton of dry solids. At 10 cents per gallon this equaled a fuel cost of $8.80 per ton.

Multiple hearth furnaces may also be operated as sludge dryers. When operated for drying, the flow of sludge and the rabbling action in multiple hearth furnaces is identical to incineration procedures. The differences are that fuel is burned at the top hearth and the gases are down-drafted to exit from the bottom hearth (also see the chapter on Heat Drying). A similar procedure, parallel flow of solids and gases, is used when incinerating skimmings in a multiple hearth furnace.

Summary - The multiple hearth unit is the most popular furnace for sewage sludge incineration because of its many advantages that include: (1) simplicity; (2) durability and low requirement for maintenance; (3) moderate operating costs; (4) ability to burn grit, screenings, skimmings, and sludge in the same unit; and (5) its flexibility to accept fluctuating loads. Also, combustion in a multiple hearth unit is "complete" (nearly 100 percent destruction of organic solids).

The disadvantages associated with the multiple hearth unit generally involve the capital cost, ash, nuisances, and explosions. Capital costs are not considered high in relation to other incinerator designs, but they could be considered high in relation to other sludge disposal techniques that use land or ocean disposal.

Theoretically, incineration should not be considered an ultimate sludge disposal technique because ash remains for subsequent handling. Lagoon space is not always conveniently located near the treatment plant site and hauling dry ash to a distant landfill area can be expensive. Unfortunately, many operating cost figures in the literature have not included a value for ash disposal. The weight of the ash may average 30 percent of the weight of the dry solids incinerated.

Nuisance conditions involving air pollution can occur, usually of a fly ash nature rather than odors. The multiple hearth incinerator effectively eliminates odors due to the high combustion temperature. Nickerson, Sawyer and Kahn, and others have generally agreed that temperatures above 1,200°F deodorize exhaust gases [291, 337]. To be safe, most designers have recommended temperatures of 1,400°F.

Fly ash can be effectively controlled by centrifugal dust collectors or water scrubbers [291]. Centrifugal collections remove 75 to 80 percent of the particles and are suitable for exhaust gas temperatures of 650 to 700°F. Water scrubbers are at least equally effective, they are less sensitive to loadings and gas temperatures, plus, they collect the condensable portion of the exit gases.

Explosions that damage equipment may occur in the multiple hearth furnace from the combustion of grease. For this reason, separate feed openings in the furnace are desirable for grease and screenings. If the unit is used for only grease and skimmings incineration, a parallel flow of feed solids and hot gases is desirable.

Incineration is being adopted by many municipalities and industries; therefore, the multiple hearth units will be installed at progressively more locations. Some improvements in the design and operation would be desirable even though the present unit operates quite satisfactorily. Recovery of heat offers one potential way of improving the economy of incineration. Research on new designs to accomplish this is advisable. Perhaps the heat could be used to condition the sludge to be incinerated. The development of additional instrumentation to control the combustion process and the development of some beneficial uses for the ash, perhaps as an aid to sludge conditioning, would be desirable.

## B. Flash Drying - Incineration

General - Flash drying - incineration processes are rarely adopted today for sewage sludge disposal. While not as popular as multiple hearth furnaces, they were installed at quite a few locations because of the flexibility of drying or incinerating the feed sludge.

Because drying of sludge for sale as a fertilizer is not often seriously considered today, this flexibility is of little interest. Flash drying-incinerators are more complex than multiple hearth units, so they do not compete very well on a straight incinerator basis.

Operation - Basically, this process involves three steps: (1) sludge dewatering in mechanical equipment, (2) heat drying, and (3) incineration.

First, the dewatered sludge feed is mixed with dry sludge to reduce its moisture content and particle size. Then, the mixture is fed into the drying system where it moves at a velocity of several thousand feet per minute in a stream of gas having a temperature of about 1,100°F. The sludge passes through this high temperature-turbulent zone in a few seconds during which time the moisture is reduced to about 10 percent. Heat dried sludge is separated from the gases and vapors in a cyclone separator.

The fluffy, dried sludge produced by the flash dryer is blown into a furnace in a manner similar to that of powdered fuel. Temperatures near 1,400°F are usually maintained for deodorization. The heat of combustion is used in the dryer operation.

The Laboon Process at Pittsburgh, Pennsylvania, incorporates flash drying-incineration of their biologically floated and concentrated primary sludge (131). Thickened liquid sludge (about 18% solids) rather than dewatered filter cake is mixed with previously dried sludge. Drying and incineration proceed in the normal fashion, except that significant quantities of auxiliary fuel are burned in the furnace along with the sludge: 0.4 pound of coal and 0.94 cubic foot of natural gas for each pound of dry sewage sludge.

Summary - Flash drying-incineration is rarely installed in treatment plants today. The lack of a fertilizer market for dried sewage sludge has eliminated one advantage for this unit, the flexibility of drying or burning. As an incineration unit, the flash drying system has the major disadvantages of complexity, potential for explosions, and potential for air pollution by fine particles. In comparative situations, it is not equal to other furnace designs.

## C. Fluidized Bed

General - A fairly recent development in sewage sludge incineration is a fluid-bed technique similar to that used in industrial processing for many years. In addition to sewage sludge destruction, this technique has been used for: "Drying, sizing, roasting, calcining and other heat treatment operations of solids-with-gases in the chemical, metallurgical, nonmetallic, food, and pharmaceutical process industries, in the pulp and paper field, and in municipal water treatment" (350). The fluidized bed process represents "complete destruction" of organic solids (at least 99%).

Theory and Operation - The term "fluidized" is used because the sludge particles are fed into a bed of fluidized sand supported by upward moving air. Sufficient air is used to keep the sand in suspension but not to carry it out of the reactor. The reactor serves as a large heat reservoir where rapid mixing of the sludge throughout the bed provides efficient contact between the sludge particles and oxygen and allows rapid heat transfer. Sludge particles are kept suspended in the moving stream of gases causing the mixture of gases and particles to behave as a liquid. The agitated sand bed retains the organic particles until they are oxidized; in addition, this reduces the size of the sludge and ash particles.

Mixing is very important in the fluidized bed process because combustion must be completed quickly and in a small combustion space. Albertson reported that: "Intense and violent mixing of the solids and gases results in uniform conditions of temperature, composition, and particle size distribution throughout the bed. Heat transfer between the gases and the solids is extremely rapid because of the large surface area available" (330). Heat required for combustion basically comes from the combustion zone where sludges are burned. Auxiliary fuel (oil or gas) is required when burning secondary sludges but, after start-up, dewatered raw primary sludge can be burned without this supplementing fuel.

The fluidized bed reactor is the main unit in the disposal system. A typical fluidized bed disposal system incorporates the following process steps: (1) solids preparation, (2) solids dewatering, (3) solids combustion, and (4) stack gas treatment (330,331).

Solids preparation starts with degritting. The two basic reasons are to prevent wear on equipment in subsequent steps and to produce a sludge with as high a volatile content as is practical. Sludge solids grinding or comminution usually follows the degritting. This procedure reduces the particle size to about 10 mm (3/8 inch), a size that can be conveniently handled by pumps, centrifuges, and the reactor feed system. Next is sludge thickening. This thickening is beneficial because it equalizes the sludge flow and increases the solids concentration. Degritting and thickening are particularly important in the second step -- dewatering. Sludge is dewatered before combustion by either a centrifuge or vacuum filter. (Both of these unit processes are discussed in other chapters). Dewatering reduces the amount of water fed to the reactor and thereby significantly improves the economics of solids combustion.

Thermal oxidation of the dewatered solids (solids combustion) is the third step. The solids are extruded into the reactor operating at a pressure of about 2 psi and a temperature of 1,400-1,500°F. They are retained in the bed until the rapid combustion reduces them to an inert ash. Sludge is not fed to the reactor until the fluidized sand bed is heated to a temperature of 1,250°F or higher. At this temperature, the sludge quickly dries and burns, thereby maintaining the bed temperature. The ash is removed from the fluidized bed by the upward flowing combustion gases.

Gases released from thermal oxidation of the solids are scrubbed and cooled in wet gas scrubbing equipment using general treatment plant effluent as the scrubbing medium. The method of disposal of inert solids contained in the scrubber water depends on local conditions. Ash solids can be separated from the liquid in a hydrocyclone, if necessary, and the liquid can be returned to the raw waste stream or recycled to the scrubber.

An instrument control system is used to control the combustion process in the reactor. In addition to standard combustion controls, the fluixized bed system uses an oxygen analyzer on the exit combustion gases. The oxygen content is continuously measured and used to automatically adjust the air rate and sludge pumping rate to the reactor. A slight excess oxygen concentration is maintained. The instrumentation system also includes an automatic shutdown safety feature in case any component fails.

Performance - The first developmental work on sewage sludge combustion was described by Albertson (330). A pilot plant at New Rochelle, New York, successfully oxidized raw primary sludge in a system similar to the standard design described above. Pilot plant tests showed that 10 to 15 percent excess air was adequate for complete combustion of the carbon and hydrogen, and smoke and odor nuisances could be eliminated at temperatures above 1,110-1,150°F.

The first commercial fluidized bed system was installed at Lynnwood, Washington, for the combustion of raw primary sewage sludge (331). After gravity thickening and centrifuge dewatering, the sludge was fed to the reactor at a solids concentration of about 35 percent. The fluidized bed reactor has been operated with 20 percent excess air or about 360 scfm at a sludge feed rate of about 210 pounds per hour. Number 2 fuel oil was used for daily reheating and as auxiliary fuel. A reactor bed temperature of about 1,300°F and a stack gas oxygen level of about 4 percent were typical operating parameters. The auxiliary fuel system was controlled by the bed temperature; fuel could be added automatically if the temperature fell below a predetermined level.

Because the reactor at Lynnwood has not been operated continuously, reheating with auxiliary fuel has been required. The fuel requirement for reheating and reheat time is a function of the shutdown period.

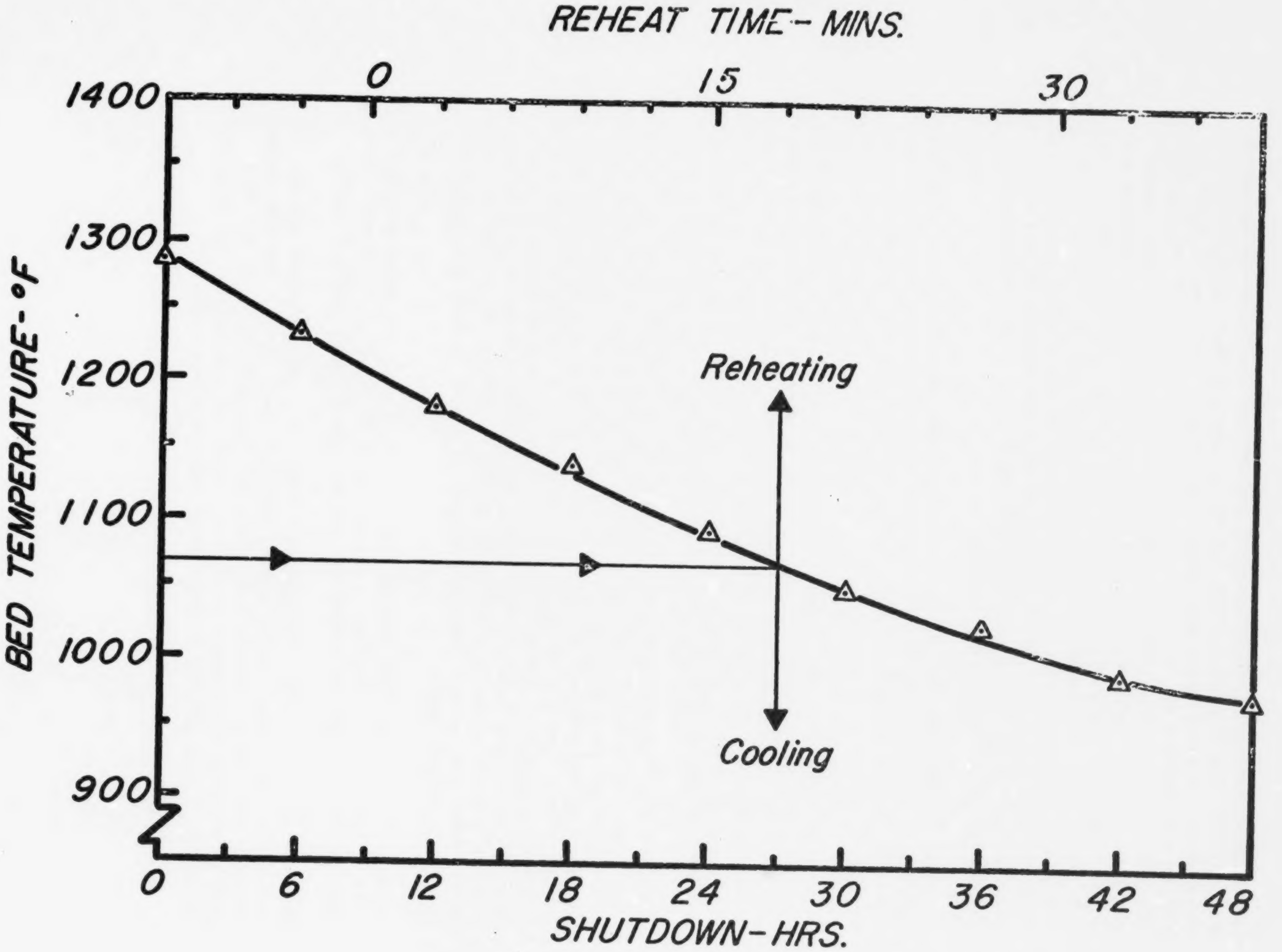
Operating power for the complete disposal system at Lynwood has been estimated to be 237 KWH per ton of dry solids. A mass spectrographic analysis of the reactor ash showed 66 percent $SiO_2$; 15 percent $Al_2O_3$; 7.5 percent CaO; and 9.25 percent ferric, magnesium, and sodium oxides (330) and 2.25% miscellaneous materials. The ash in the scrubber water was removed by a hydrocyclone and discharged to a lagoon.

The East Cliff Sanitary District sewage treatment plant in California installed a fluidized bed process in existing facilities. A digester was converted to a thickening tank and other added equipment was placed into existing buildings (317, 331). Raw primary sludge was burned with a small auxiliary fuel demand in a residential area with few odor problems. Auxiliary fuel was required only during Monday morning start-ups because the bed temperatures at shutdown exceeded 1,400°F and the overnight loss of temperature was less than 150°F or about 7-8°F per hour. Sludge combustion could be started immediately the following morning.

Figure 19.II describes typical bed temperatures, shutdown periods and reheat time (331). Maximum pressure within the unit is about 3.5 psig. Make-up sand is added to the bed about once every 6 weeks.

Stack gases have been analyzed and they meet California's strict air pollution codes. Dust quantities are very small, and the gases contain no organic by-products from the combustion process. Off-gases from the thickening tank are collected and fed to the reactor, eliminating any possible odors from that process step.

Figure 19.II



Cooling and heating times of a small reactor for various reactor temperatures.

(Reprinted by permission Dorr-Olive, Inc.)

Economics - Capital and operating costs for the fluidized-bed combustion system have been reported for most of the installations in service. At Lynnwood, Washington, capital and operating costs were compared with single stage digestion followed by land disposal of the liquid sludge. Albertson listed the following cost data (330):

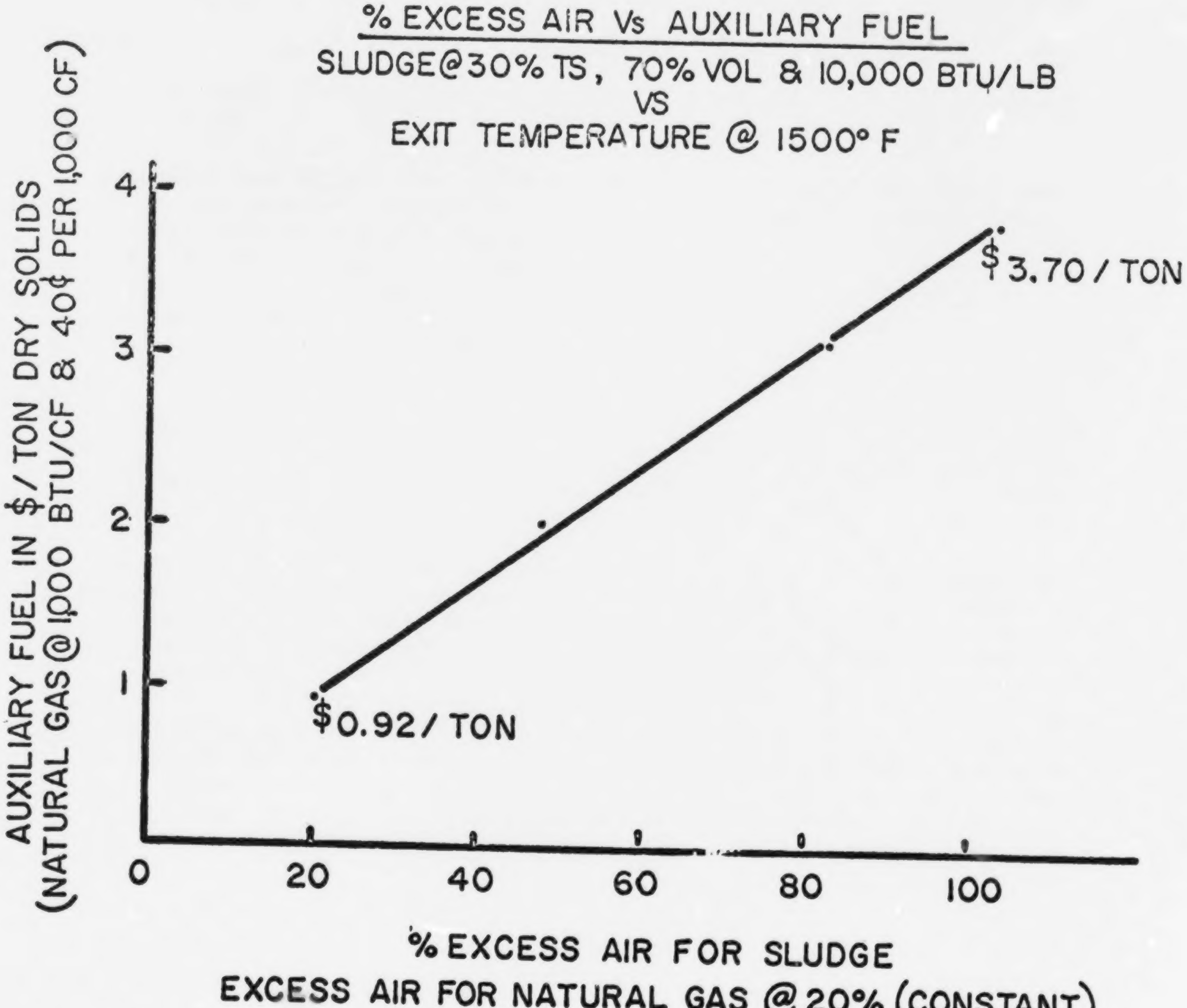
| | Combustion System($/Ton) | | Digestion System($/Ton) | |
|---|---|---|---|---|
| | 8,000 Pop. | 22,000 Pop. | 8,000 Pop. | 22,000 Pop. |
| Capital Costs (25 year amortization at 4% interest) | $15.00 | $15.00 | $7.50 | $7.50 |
| Operating Costs | $20.44 | $11.38 | $38.48 | $26.80 |
| Total | $35.44 | $26.38 | $45.98 | $34.30 |

Labor costs for both combustion and digestion are similar and represent a major portion of the total operating cost figure. Hauling the digested liquid sludge to land disposal areas accounts for the significant difference between the two cost figures. Albertson used a unit cost figure of 0.9 cent per gallon of liquid sludge. In the combustion system, power and fuel accounted for 21.7 percent of the operating cost at the 8,000-population level and 38.6 percent at the 22,000 level. Power was computed at 1 cent per KWH and fuel at 12 cents per gallon.

At the East Cliff Sanitary District plant, California, an operating cost of approximately $25.32 per ton has been reported (317). This figure includes: (1) $2.50 per ton for fuel, (2) $4.47 per ton for power, and (3) $18.35 per ton for labor.

The economy of the fluidized bed system is a function of the percentage of excess air; therefore, automatic controls are used to keep the excess air at about 20 percent which minimizes the loss of input heat and reduces the fuel demand. Figure 19.III shows the impact of excess air on the cost of fuel in sludge incineration (462). An air preheater is an optional piece of equipment which, according to Walter and Millward can reduce the auxiliary fuel cost (462). He used an example where air preheated from 70°F to 1,000°F allowed a reduction in fuel costs from $9 per ton to $3.50 per ton. The air preheater could represent 15 percent of a fluidized-bed plant's investment, so its cost must be compared with the economics of using additional auxiliary fuel.

Figure 19.III



**The impact of excess air on the cost of fuel in sludge incineration.**
(Reprinted by permission Dorr-Oliver, Inc.)

Reactor-feed solids concentration is the major factor in combustion economy. The drier the cake from vacuum filtration or centrifugation, the lower the cost of operation. Figure 19.IV shows the effect of cake moisture content on the cost of auxiliary fuel (462). While the fluidized bed reactor can handle a 10 percent solids feed, it is uneconomical to eliminate the sludge dewatering step due to the required increase in auxiliary fuel. Through the use of thickening and degritting processes, the fluidized bed system produces sludges for combustion having high volatile solids and a minimum of excess water. This combined with air preheating and close control of excess air optimizes combustion efficiency. Figure 19.V shows the effect of cake volatile solids concentration on the cost of auxiliary fuel for sludge incineration.

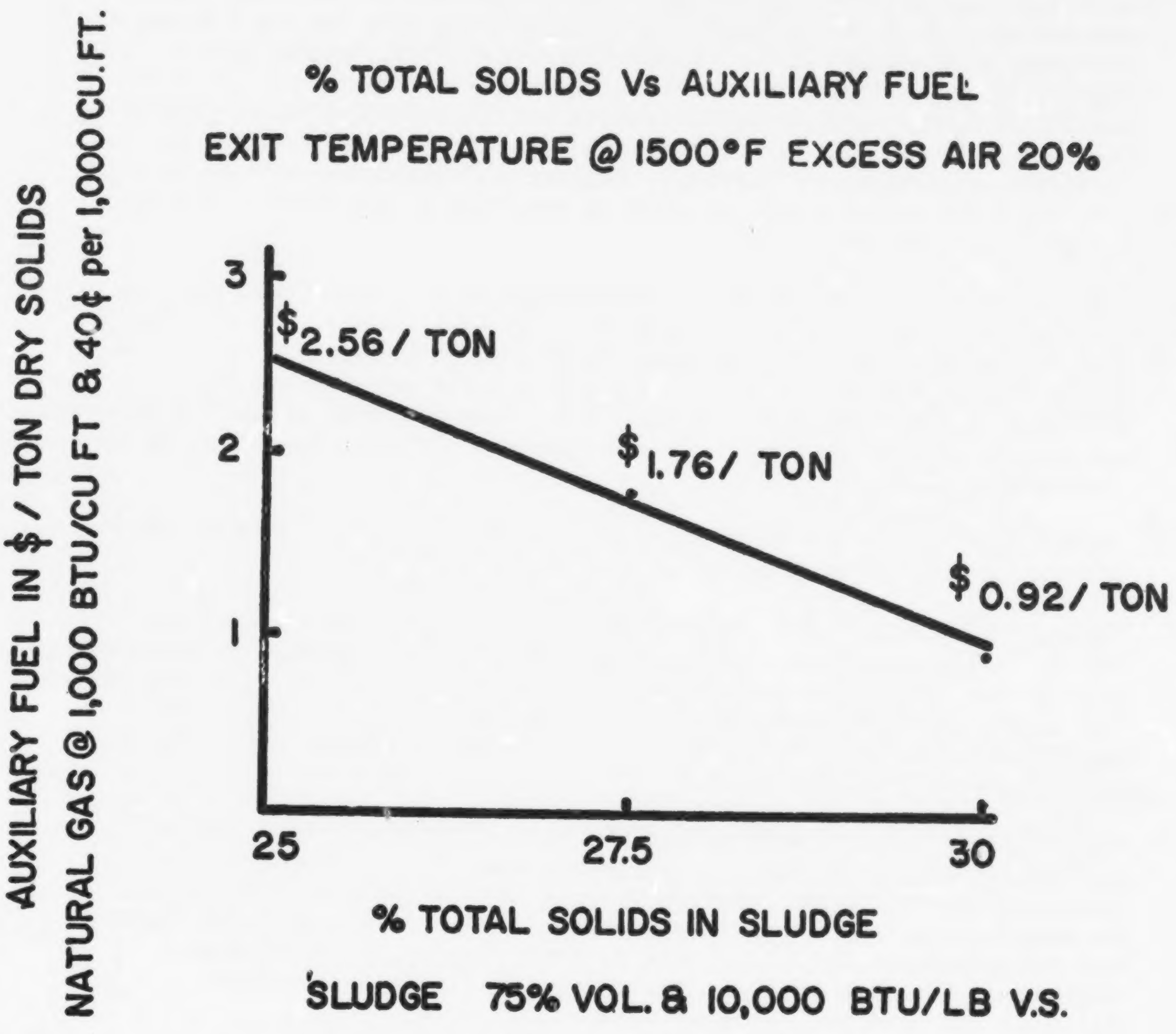
There are, of course, increased operating costs if chemicals must be used in the dewatering step. The cost for fuel, power, and chemicals will be about $5 per ton for handling raw primary sewage sludge in a fluidized bed system and $15 to $18 per ton for raw primary and secondary sludge. Most centrifuges have been operated without chemicals, but vacuum filtration almost always requires chemical conditioning of the sludge.

The annual cost of the fluidized bed system appears to be from $25 to $50 per ton of dry solids.

Summary - The advantages claimed for the fluidized bed combustion system include: (1) small area requirement when compared with digesters, lagoons and sand beds; (2) high degree of organic sludge oxidation with low excess air requirements; (3) low operating expense; (4) no air pollution nuisance, and (5) automatic control of combustion to give optimum results (331).

Temperatures from 1,250°F to 1,400°F have eliminated stack gas odor. The use of automatic devices to control combustion after start-up maintains optimum combustion conditions with a minimum of attention. An oxygen analyzer in the stack controls the air rate into the reactor and the auxiliary fuel feed rate is controlled by a temperature recorder. Shutdown controls for emergency situations further decrease the need for operator attention.

Figure 19.IV



**The effect of moisture content on the cost of sludge combustion.**
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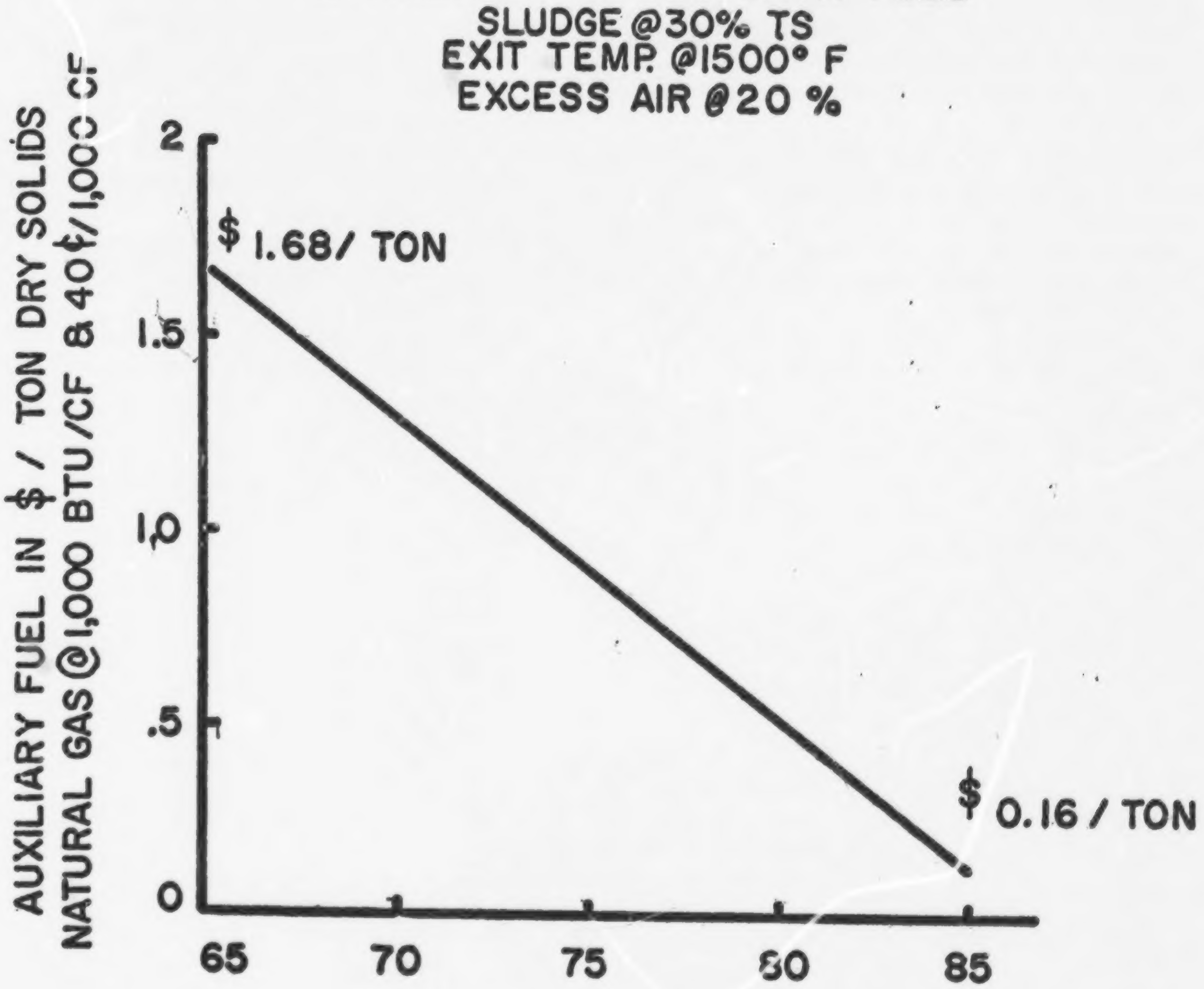
Figure 19.V



The effect of the percent of volatile solids on the cost of auxiliary fuel for sludge incineration

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Burning sludge in a fluidized bed or any other system may not always be the most economical solution to ultimate sludge disposal. However, incineration is becoming increasingly popular. More accurate fluidized bed cost and performance data are needed and will become available. Current information indicates that the fluidized bed system is applicable to cities as small as 10,000 population. Several years ago, mechanical dewatering and incineration were considered feasible only for cities with a population of at least 25,000. The major operational problem with the fluidized-bed system seems to be the centrifugal dewatering step. (Centrifuge operation and economics are discussed in the section on dewatering.)

In general, the fluidized-bed systems are operating satisfactorily and they appear to be competitive with other incineration techniques if deodorization to 1,400°F is required for effluent gases. If deodorization of effluent gases is not required, fluidized bed systems could be somewhat more expensive than multiple hearth furnaces.

## D. Atomized Spraying

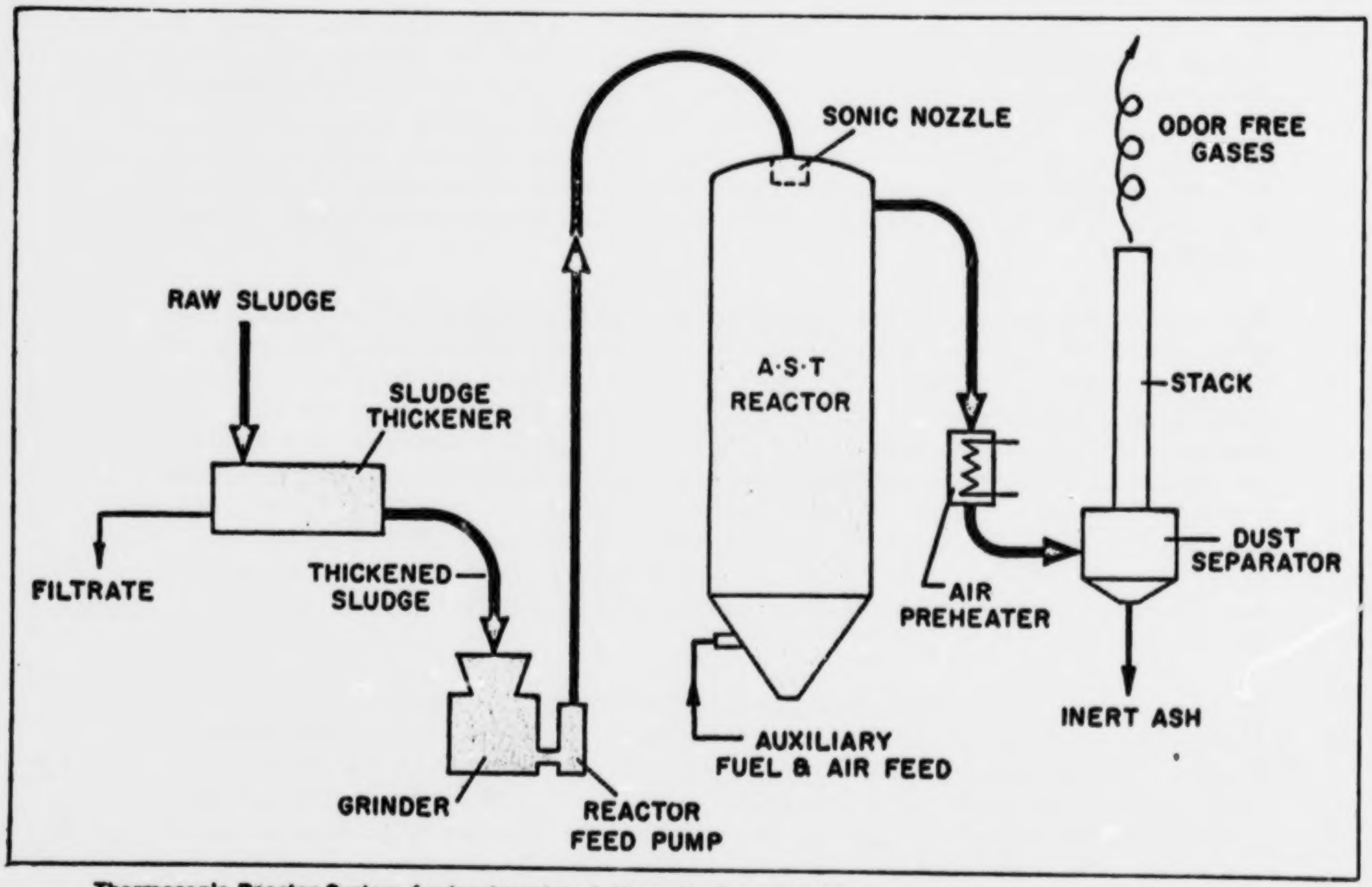
General - A recently developed sludge destruction technique referred to as "spray evaporation" has received much publicity (53). It has also been designated as the Atomized Suspension Technique (AST) and the Thermosonic Reactor System. The process has some resemblance to spray drying techniques discussed since 1872. In general, the atomized suspension technique has been designed for high temperature-low pressure thermal processing of wastewater sludges. Sludges are reduced to an innocuous ash, and bacteria and odors are destroyed.

Theory and Design - Basically, the process includes the following steps: (1) thickening the feed sludge to a range of 4.5 to 11 percent solids, preferably greater than 8 percent; (2) grinding the sludge to reduce the particle size, generally to less than 25 microns; (3) spraying the sludge into the top of a reactor to form an "atomized suspension"; (4) drying and burning the sludge within the reactor; and (5) collecting and separating the ash from the hot gases. Details of the process have been described in numerous literature references (53, 309, 314, 316). Figure 19.VI shows the basic components of the system (316).

The unique features of the atomized sludge incineration process start with a sonic atomizer that produces a mist and fine particle spray at the top of the reactor. The reactor feed pump supplies the required atomizing prossure of 20 to 40 psig. Within the top zone of the reactor the atomized suspension is formed quickly because the walls of the reactor are very hot. The atomized sludge particles pass down through the inner shell of the reactor. Heat is supplied by hot gases and dust passing at high velocities up the annulus of the reactor. This heat is created by an oil or gas fired burner at the bottom of the reactor plus the exothermic oxidation of sludge particles also at the bottom.

As the sludge particles pass downward through the reactor, the following actions occur: atomization heating to 212°F, evaporation at 212°F, heating to combustion temperatures, and high temperature combustion. At a temperature of about 600°F, the dried sludge solids ignite contributing to gas temperatures that ultimately reach 2,000°F. The destruction of odor components is essentially instantaneous and complete at this temperature. Evaporation, combustion, and gasification is not inhibited in this system because it operates at low pressure. Heat transfer in the annulus results from convection to the metallic walls and then by radiation to the atomized sludge particles. The high velocity of the upward stream in the annulus serves two functions: first, it increases the heat transfer, and, second, it suspends the dry fine dust so that it is carried out of the reactor.

Figure 19.VI


SONIC NOZZLE
ODOR FREE GASES
RAW SLUDGE
A·S·T REACTOR
STACK
SLUDGE THICKENER
FILTRATE
THICKENED SLUDGE
DUST SEPARATOR
AIR PREHEATER
INERT ASH
AUXILIARY FUEL & AIR FEED
GRINDER
REACTOR FEED PUMP

Thermosonic Reactor System for treatment and disposal of raw sludge.

(Reprinted by permission of Water and Wastes Engineering)

Following the reactor combustion step, there is an air preheater-heat recovery system, a cyclone scrubber to remove dust particles from the gas, and a simple stack for venting the solids-free combustion gases.

The system could be thermally self-sufficient after start-up. Whether supplemental fuel would be needed along with the fuel provided by the dried organic compounds in the waste sludge depends on the type and concentration of the sludge and on the amount of excess air used.

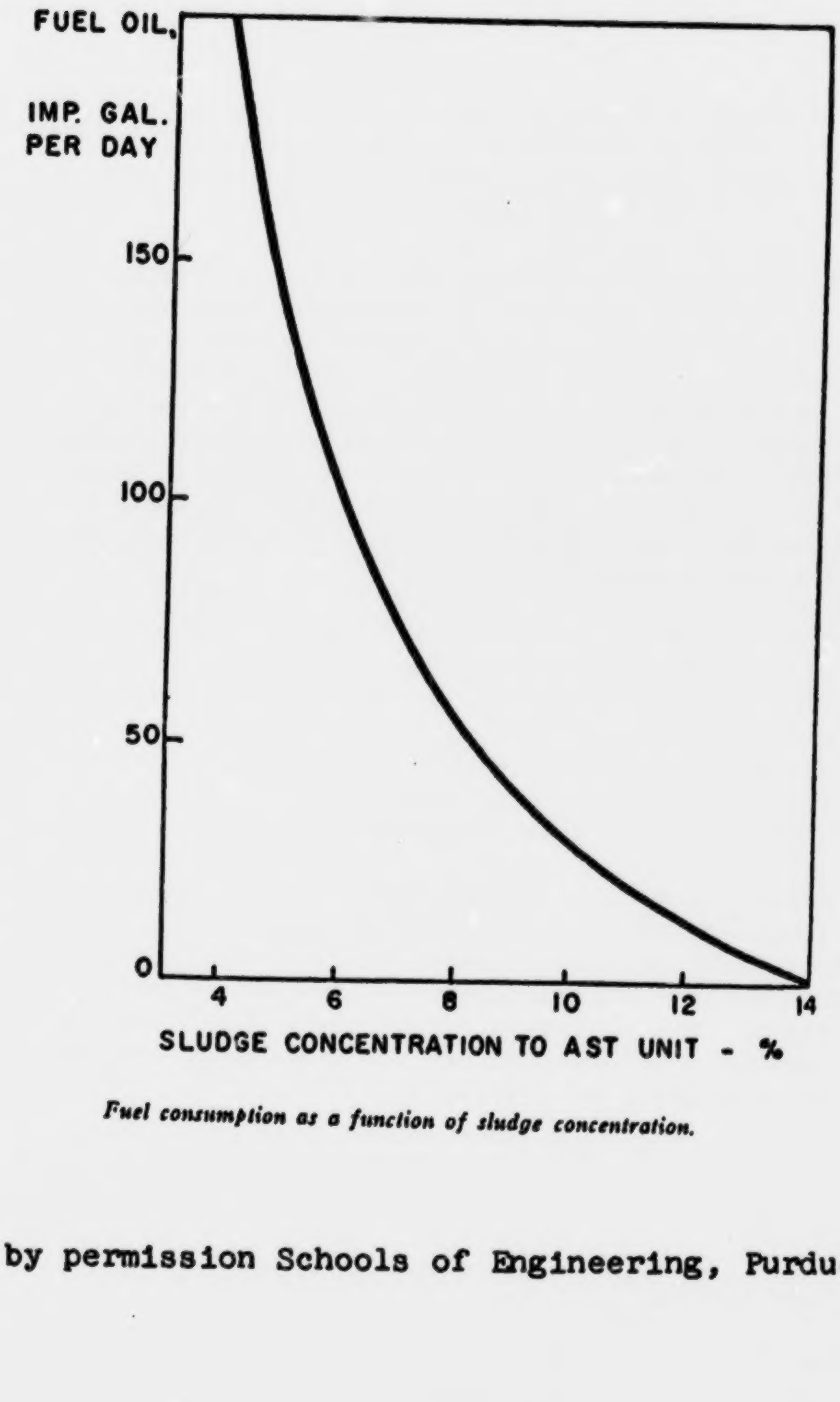
Parameters - Various parameters that are important in the design and performance of atomized suspension incineration have included: sludge type, sludge solids concentration, amount of excess air used, pressure in the reactor, and sludge particle size.

The sludge solids concentration necessary for self-sustaining combustion is a function of the type of sludge and the excess air used. Sewage sludges would probably not be thermally self-sufficient unless first dewatered in mechanical equipment. It has been estimated that a raw sludge having a heating value of 8,780 B.t.u. per pound of dry solids would have to be thickened to 14 percent to be thermally self-sufficient (309). Achieving this concentration may be more expensive than burning oil or gas as a supplemental fuel. Figure 19.VII relates the necessary fuel consumption as a function of raw sewage sludge solids concentration (309).

Particle size distribution has been an important factor in sludge stoppages in lines and in the atomizing nozzle; it also affects combustion. The rates of evaporation and heat transfer in the reactor are directly proportional to the particle volume (316). The system has been operated at a pressure equal to less than 30 inches of water to prevent leakage from the equipment and to insure no inhibition of evaporation and gasification.

Application and Performance - According to the manufacturer, atomized suspension techniques have been versatile to the point of being applicable for "Combinations of evaporation, drying, pyrolysis, oxidation, and chemical reactions" (314). In addition to the demonstrated use for processing sewage sludge, it was claimed to be useful for chemical recovery in the pulp and paper industry and for oxidizing organic wastes from the food industry.

Figure 19.VII



*Fuel consumption as a function of sludge concentration.*

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Martin and Bryden discussed pilot plant performance of the atomized suspension technique using raw primary sludge as the reactor feed (288). A 4.5 to 6 percent sludge was concentrated in a cyclone evaporator to 11 percent prior to injection into the reactor at a feed rate of 750 pounds per hour. The pressure to the atomizing nozzles was 30 psi and the reactor wall temperature was 1,400-1,450°F. A heat supply of 970,000 B.t.u. per hour, or 1,300B.t.u.per pound of sludge, was required to produce 36 percent useful work. The flue gases accounted for 46 percent of the heat supply.

Beaconsfield, Quebec, installed an atomized suspension facility for the combustion of raw primary sewage sludge. An 8 to 10 percent thickened sludge was fed to a reactor having a maximum temperature of 1,400°F. After a 1-minute detention time, the system produced an effluent consisting of odorless gases, condensed water, and an inorganic ash. About 400 pounds of ash per day have been produced from 12,000 pounds of sludge (53, 66, 298).

A U.S. chemical company evaluated the spraying of thickened activated sludge into a conventional furnace at a power generation plant. Nearly 8 tons per day of a 2.2 to 2.6 percent sludge was burned along with coal, the usual fuel. Plugging of the sludge feed device was a major operational problem but this was solved by using a strainer to eliminate oversized solids (332).

Economics - Being a new process for sludge handling, very little capital and operating cost data have been available. MacLaren reported that the Beaconsfield capital cost as $70,000 for the sludge thickening tank, AST equipment, and associated buildings (53). The design feed rate was 0.65 ton per day; therefore, the equivalent capital cost was $100,000 per ton. A capital cost of $45,000 per ton of capacity for a 50-ton-per-day unit was also reported by MacLaren. He quoted general capital costs of $15 to $30 per ton (30 year amortization at 5%) and operating costs based on Beaconsfield experience of $15 to $25 per ton. Total capital and operating costs have been, therefore, estimated to be from $30 to $55 per dry ton of solids. The recovery of additional heat for beneficial uses such as self-sustained combustion could lower costs, if this recovery were determined to be feasible.

Summary - In general, the atomized suspension combustion technique has been claimed to offer the following advantages: (1) versatility in sludge handled; (2) continuous and rapid conversion of raw sludge to innocuous ash, steam, and $CO_2$; (3) small space requirement; (4) closed system operation; (5) little or no nuisance conditions; and (6) flexibility in accomplishing drying or complete oxidation of the sludge solids (309).

A discussion of disadvantages may be premature because of the newness of this system. However, it has been estimated that the cost will be somewhat higher than conventional incineration processes due to maintenance and the need for supplemental fuel oil or gas. Thermal self-sufficiency is possible with primary sludge at solids concentrations of 20 to 25 percent, but this material would be difficult to handle; so, fuel must be used along with the more dilute sludges (316). Capital costs do not appear to be less than for other incineration techniques. The AST process does, however, have an advantage over the Zimpro wet oxidation process in that the operating pressures are much lower. A more valid evaluation will be possible after additional plant experience has been gained. The possibility of incinerating a dilute sludge, thereby eliminating costly dewatering steps, is very attractive. Continued research and development of atomized spray systems should be encouraged.

## E. Wet Oxidation

General - The terms wet oxidation, wet incineration, and wet combustion have all been applied to a commercialized process commonly called the Zimmerman or Zimpro Process. This process refers to the oxidation of sludge solids in an aqueous medium by applying heat and pressure. Wet oxidation can accomplish different degrees of organic matter destruction depending on the temperature and pressure applied.

This section will include only "complete destruction" of putrescible solids which is often defined as at least 90 percent reduction. At this lever, wet oxidation competes with other incineration techniques such as multiple hearth furnaces, fluidized beds, atomized suspension processes, flash drying and incineration.

Less than "complete destruction" of organic solids by the wet oxidation process is discussed in the sludge conditioning section because it essentially competes with digestion and chemical sludge conditioning prior to dewatering.

Theory - An A.S.C.E. Committee report gave a good thorough discussion of wet oxidation theory (311). Basically, it stated that waste sludge organic solids are "Chemically oxidized in an aqueous phase by dissolved oxygen in a specially designed reactor at elevated temperature and pressure." Figure 19.VIII describes a typical flow sheet for the wet oxidation process.

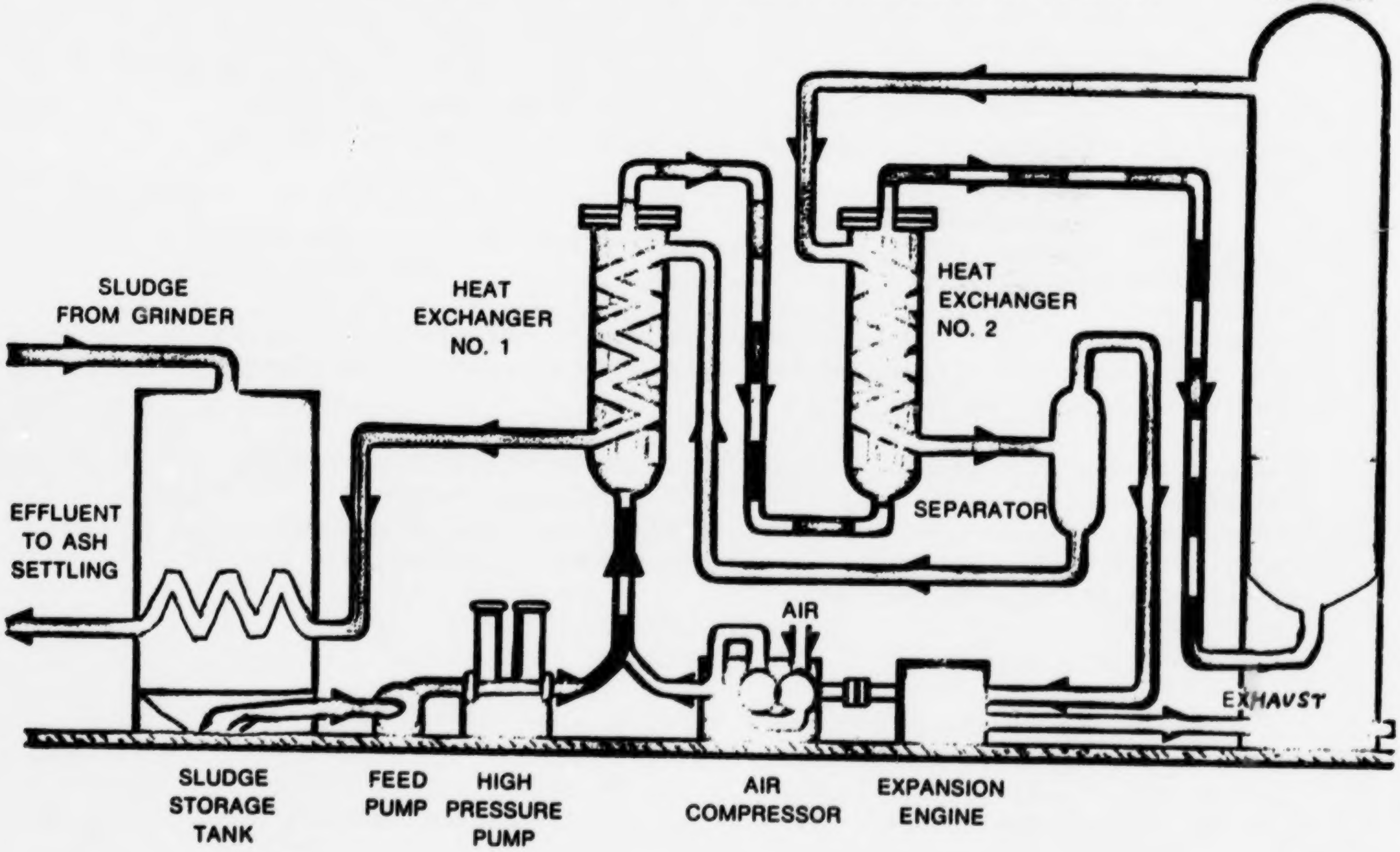
Basic equipment includes a reactor, air compressor, heat exchanger, and high pressure sludge pump (66). Other related equipment could include sludge concentration-storage tanks, sludge grinders, solid-liquid separation tanks, power generating equipment, and vacuum filters for wet ash dewatering.

In general, the process steps are as follows:

1. Thickened sludge is passed through a grinder to reduce the particle size.
2. The sludge is pressurized to the necessary operating level.
3. The sludge is preheated in heat exchangers by reactor gases, steam, and water.
4. Air is combined with the preheated sludge and the resultant mixture is injected at the bottom of the reactor.
5. Oxidation occurs as the sludge-air mixture follows a baffled path through the reactor.
6. The reactor effluent is cooled while passing through the heat exchangers.
7. A gas-liquid separation is made followed by an ash-liquid separation.
8. The separate ash is dewatered in lagoons, on vacuum filter', or by some other means.

Figure 19.VIII

FLOW DIAGRAM OF ZIMPRO WET AIR OXIDATION UNIT


REACTOR
SLUDGE FROM GRINDER
HEAT EXCHANGER NO. 1
HEAT EXCHANGER NO. 2
EFFLUENT TO ASH SETTLING
SEPARATOR
AIR
EXHAUST
SLUDGE STORAGE TANK
FEED PUMP
HIGH PRESSURE PUMP
AIR COMPRESSOR
EXPANSION ENGINE

(Reprinted by permission Zimpro Division of Sterling Drug, Inc.)

In the above process insoluble organic matter is converted to soluble organic compounds which are then oxidized to form mainly $CO_2$ and water. Organic nitrogen compounds are converted to ammonia, and sulfur to sulfates (304).

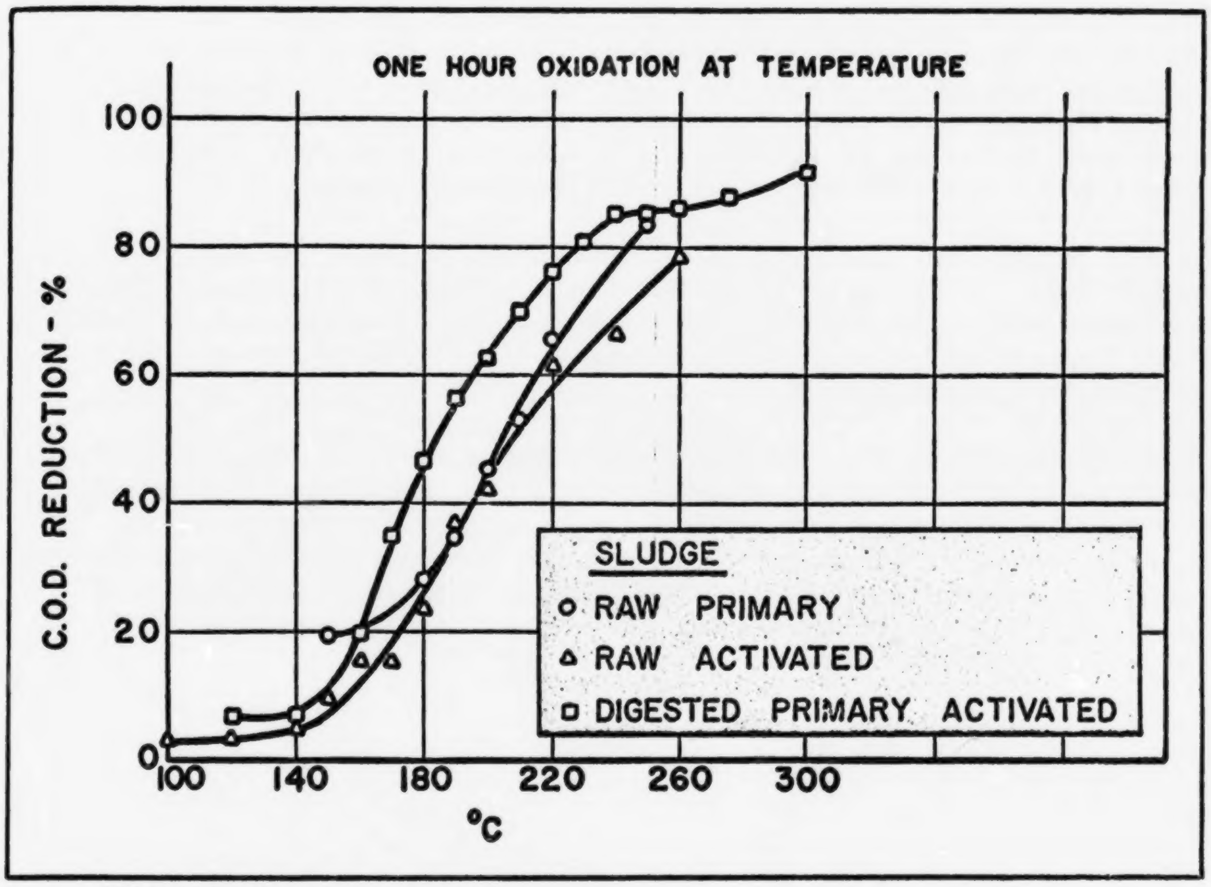
Parameters - Four important parameters control the performance of wet oxidation units: temperature, air supply, pressure, and feed solids concentration.

The degree and rate of sludge solids oxidation are significantly influenced by the reactor temperature. A much higher degree of oxidation and shorter reaction times are possible with increased temperatures. Hurwitz and co-workers showed this in their data presented in Figure 19.IX relating C.O.D. reduction with temperature (100°C to 300°C) for a number of different sludges (304).

As is the case in conventional incinerators, an external supply of oxygen (air) is required to attain nearly complete oxidation. The air requirement for the wet oxidation process is determined by the heat value of the sludge being oxidized (311); and by the degree of oxidation accomplished.

Thermal efficiency and process economy are a function of air input, so it is important that the optimum amount be determined. Because the input air becomes saturated with steam from contact with reactor water, it is important to control the air also to prevent excessive evaporation of the water. Table 19.2 describes the heat value of different materials and the air utilization in the oxidation process (293).

Figure 19.IX



**COD reduction vs. temperature.**

(Reprinted by permission Water and Sewage Works)

## Table 19.2

| Material | Heat Value (B.t.u./lb) | Oxygen Utilization (lb/lb Material) | Air Utilization (lb/lb Material) | Heat in Terms of Air Use (B.t.u./lb air) |
|---|---|---|---|---|
| Acetic Acid | 6,270 | 1.07 | 4.6 | 1,365 |
| Carbon | 14,093 | 2.66 | 11.53 | 1,220 |
| Casein | 10,550 | 1.75 | 7.55 | 1,395 |
| Ethylene | 21,460 | 3.42 | 14.8 | 1,450 |
| Fuel Oil | 19,376 | 3.26 | 14.0 | 1,380 |
| Hydrogen | 61,000 | 7.937 | 34.34 | 1,780 |
| Lactose | 7,100 | 1.13 | 4.87 | 1,455 |
| Oxalic acid | 1,203 | 0.178 | 0.77 | 1,565 |
| Pyridine | 14,950 | 2.53 | 10.9 | 1,370 |
| Semi-Chemical solids | 5,812 | 0.955 | 4.13 | 1,410 |
| Sewage sludge,primary | 7,820 | 1.334 | 5.75 | 1,365 |
| Sewage sludge, activated | 6,540 | 1.191 | 5.14 | 1,270 |
| Waste sewage sludge solids | 7,900 | 1.32 | 5.70 | 1,385 |

Oxidation in an aqueous system requires sufficient pressure in the reactor to condense the water vapor, because temperatures are above 212°F. Operating pressures have varied from 150 to 3,000 psi, depending on the size of the plant and the degree of oxidation desired(326).

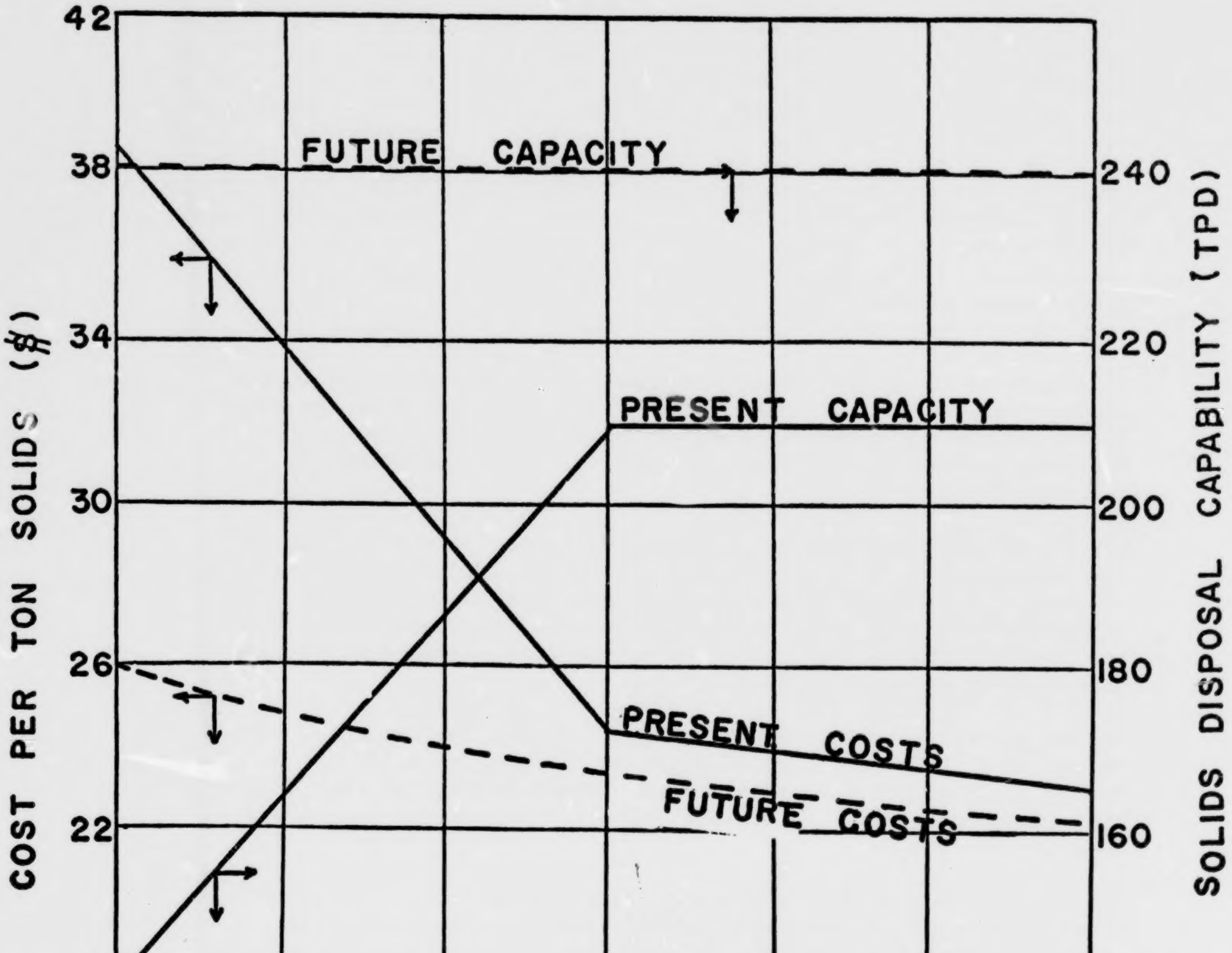
Ettelt and Kennedy reported on the significance of the feed solids concentration, as it applies to wet oxidation at the Chicago Sanitary District(56). Figure 19.X shows that the cost can be reduced by $15.50 per ton if the feed sludge solids are thickened from 3 to 6 percent(56). Future modifications of the heat exchangers and pump capacity may reduce this cost further.

Thickening the sludge feed is important to keep the oxidation self-sustaining. After an original estimate of 2,350 to 3,000 B.t.u. per gallon of feed as being satisfactory, it was determined that 4000 B.t.u. per gallon was necessary for self-sustained combustion at the Chicago facility.

A typical design problem for a wet oxidation facility involves the determination of the required pumping capacity, the proper size of reactors and heat exchangers, and the size of compressors to deliver the optimum quantity of air(307).

Figure 19.X

EFFECT OF FEED SOLIDS CONCENTRATION ON CAPACITY AND COSTS OF WET AIR OXIDATION PROCESS AT CHICAGO



(Reprinted by permission from Vol. 38, No. 2, p. 250 Feb. 1966, J. Water Pollution Control Federation)

Application and Performance - Hurwitz, et al, reported on the successful application of the wet oxidation technique to many types of sewage sludges (304). They stated that all sludges, whether oxidized to a low or high degree, were suitable for ultimate disposal because they were sterile, biologically stable, and had good settling and dewatering characteristics. Teletzke said that wet air oxidation was also applicable to industrial organic sludges (305). He thought that this process was particularly applicable to paper and textile-mill sludges because the oxidation converts nitrogen to ammonia which can be returned in the effluent liquid to a biologic treatment process where it serves as an added nutrient.

One of the first technical articles describing wet oxidation of sludge was written by Moran and co-workers (294). They oxidized raw primary sludge in laboratory experiments, using oxygen gas at elevated temperatures and pressures. The feed sludge, containing 4.8 to 6.4 percent solids, was macerated in a blender and oxidized in an autoclave. Temperatures from 150°C to 300°C and oxygen pressures from 300 to 1,000 psia were investigated. These temperatures and pressures were maintained for 2 hours.

At 150°C and 300 psi, less than 10 percent of the initial carbon was converted to $CO_2$. However, the sludge was suitable for further processing because the odor and slimy nature of the solids were eliminated.

At 250°C and 1,000 psi, 75 percent of the initial carbon was converted to $CO_2$. An essentially odorless and colorless liquid remained, having an insoluble residue containing less than 1 percent of the initial carbon. Moran and his co-workers speculated that complete conversion to $CO_2$ might be possible: at higher temperatures or pressures, with better contact between the oxygen and waste liquid, or with the use of a catalyst (294).

Data from pilot-plant operations at the Chicago Sanitary District indicated that 90 percent of the organic matter in sewage sludge can be oxidized at 500°F and 1,200 psig. Also, it was concluded that if the feed solids concentration is high enough, sufficient thermal energy can be recovered to operate the entire wet oxidation process (311).

Full-scale plant data showed that the C.O.D. can be reduced by 75 to 80 percent at temperatures near 525°F and pressures about 1,750 psig (312, 326). The feed sludge has been a raw primary-activated combination having a solids concentration of about 3 percent. Sludge volatiles have been about 65 percent and the B.t.u. per gallon about 2,000, far below the self-sustaining combustion goal of 4,000 B.t.u. per gallon. Power requirements have been 2,000 KW per 50 tons of sludge per day.

Wet oxidation plant residues have been discussed on the basis of pilot plant (299) and full-scale plant studies (312). Hurwitz and Dundas reported that the end product from a pilot plant was high in ammonia and volatile acids from the oxidation of nitrogen and carbon sludge constituents (299). They determined that the wet oxidation effluent had a B.O.D. between 5,400 and 8,400 ppm, which was a 60 percent reduction from the B.O.D. of the original liquid sludge. The settleable ash contained 10 to 12 percent of the volatiles after 1 hour settling, the volatile content of the dried ash was 15 percent. Exhaust gases from the pilot plant contained nitrogen, $CO_2$, and a trace of hydrocarbons. Hurwitz and Dundas observed that the reactor effluent was amenable to aerobic biological treatment. Table 19.3 by Hurwitz and Dundas (299) described specific chemical characteristics of wet oxidation reactor effluent. They also analyzed the washed and dried effluent ash; these data are listed in Table 19.4 (307).

Table 19.3

| Volatile Solids | Reactor Effluent | | | | Settled Effluent | Effluent Ash |
|---|---|---|---|---|---|---|
| Concentration Range (Percent) | $NH_3$- N (mg/l) | Org. N (mg/l) | Volatile Acids as acetic (mg/l) | COD (mg/l) | COD (mg/l) | COD* in ash (mg) |
| 2.00-2.99 | 1,370 | 368 | 3,200 | 10,200 | 8,300 | 1,900 |
| 3.00-3.99 | 1,625 | 425 | 3,480 | 13,200 | 9,800 | 3,400 |
| 4.00-4.99 | 1,640 | 548 | 3,980 | 16,600 | 11,600 | 5,000 |

*COD left in ash settled from 1 liter of reactor effluent.

Table 19.4

Typical Analysis of Ash from Wet Oxidation Process

| | Percent* |
|---|---|
| Iron (Fe) | 4.92 |
| Silicon (Si) | 3.78 |
| Potassium (K) | 0.76 |
| Manganese (Mn) | 0.025 |
| Calcium (Ca) | 0.87 |
| Aluminum (Al) | 3.90 |
| Zinc (Zn) | 0.04 |
| Copper (Cu) | 0.24 |
| Magnesium (Mg) | 0.03 |
| Phosphorus (P) | 2.62 |
| Boron (B) | 0.03 |
| Nickel (Ni) | 0.01 |
| Sodium (Na) | 0.12 |
| Specific gravity | 2.23 |

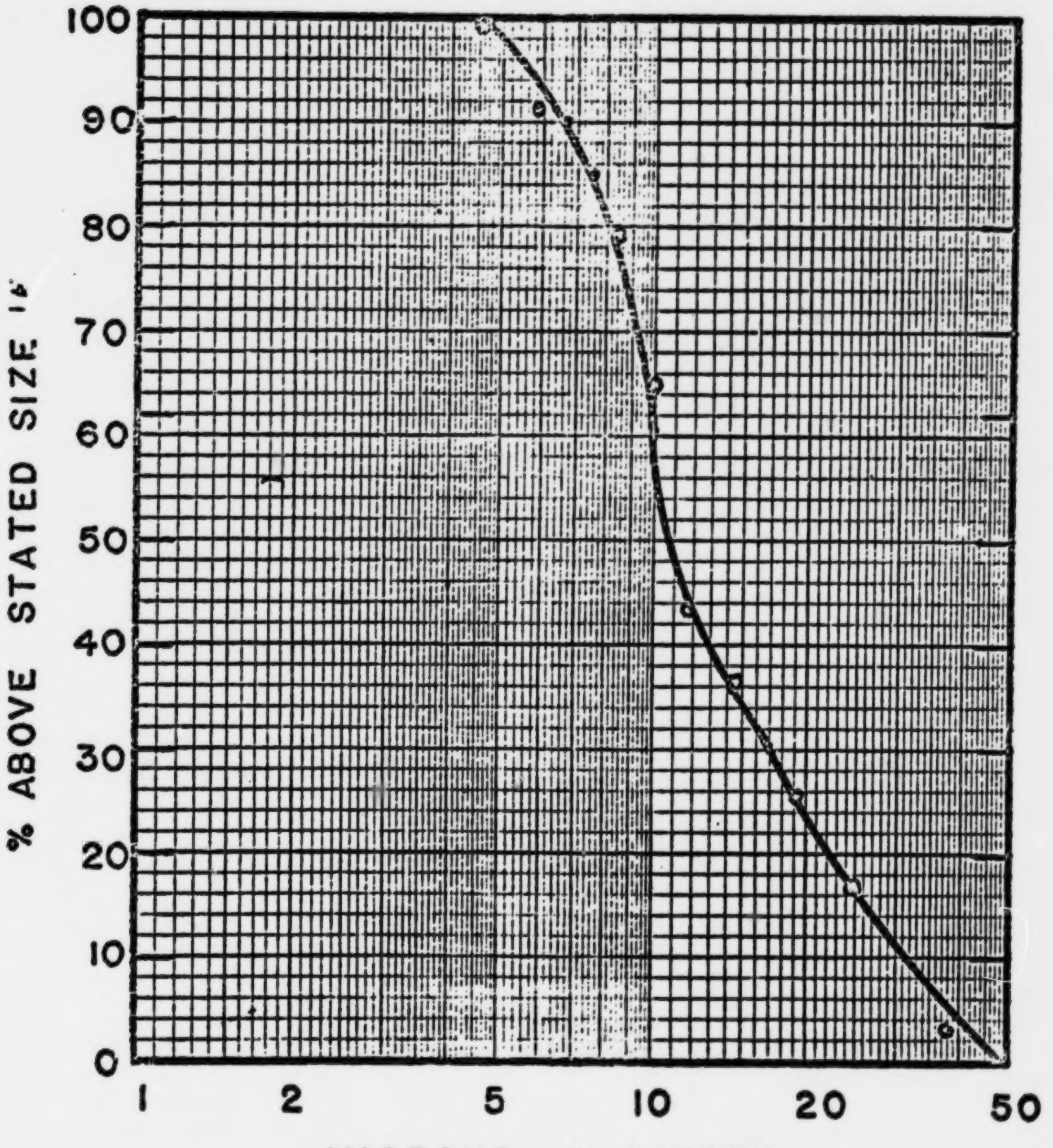
*Metals determined spectrometrically.

Walters and Ettelt made a very thorough study of dewatering the wet oxidation ash by vacuum filtration and centrifugation (327). Their search for a technique to dewater the ash was prompted by the inadequacy of the current ash lagoon disposal system. First, they determined that sedimentation followed by sand-bed drying was impractical due to weather restrictions. The next step was to characterize the ash. For the Chicago facility, it was determined that ash dewatering properties depend on the degree of sludge oxidation and on the nature of the material fed to the wet oxidation process. The average ash particle has a density of 2.1 grams per cubic centimeter and a size range between 7 and 44 microns. Figure 19.XI describes the ash particle size distribution.

Because solids concentration before dewatering was usually advisable, Walters and Ettelt (327), conducted batch gravity settling tests and concluded that a 10 percent wet oxidation slurry could be attained in 6 hours. The average wet oxidation effluent carried about 1.5 percent solids in suspension.

Laboratory bench and pilot-plant vacuum filtration tests indicated that the wet oxidation ash could be satisfactorily dewatered on conventional filtration equipment. A belt vacuum filter with continuous washing of the filter media produced a constant filtration rate of 5.6 pounds per square foot per hour of cake when the feed solids concentration was 9.4 percent. The dewatered cake contained 40.5 percent solids and the filtrate solids varied from 0.16 to 0.6 percent. No chemical conditioning of the slurry was required.

Figure 19.XI ZIMPRO ASH PARTICLE SIZE DISTRIBUTION



(Reprinted by permission Schools of Engineering, Purdue University)

The pilot-plant centrifuge tests run by Walters and Ettelt(327) on wet oxidation ash determined that solids captures of 60 to 70 percent could be obtained, starting with a 10.8 percent solids feed. The dewatered ash contained 52 to 56 percent solids. Solids captures greater than 99 percent were possible with the use of reasonable doses of an anionic polyelectrolyte; however, the cake solids concentration dropped to 30 to 40 percent.

The long term goal at Chicago has been expressed as the desire to use the effluent in such a way that it reduces the cost of operation. In this regard, Koenig has suggested the use of wet oxidation ash to make various ceramic products(54).

Wet oxidation of raw primary sludge at Rye, New York, has been described by Harding and Griffin(295). The Blind Brook treatment plant at Rye achieved a 90 percent reduction of insoluble organic matter by operating at a temperature of 237.8°C and a pressure of 750 psi. This is a small plant having a sewage sludge solids concentration from 5 to 7 percent and a volatile solids concentration of about 65 percent. The wet oxidation facility has been operated intermittently on a 7 days on, 7 days off, schedule(72, 295). Auxiliary fuel has been used only when starting the unit.

The oxidized sludge (ash) had an organic content of 18.6 percent during the first year's operation (1964). After cooling and solid-liquid separation, the B.O.D. of the supernatant effluent averaged 8,400 ppm. This represented only a small quantity in comparison with the entire treatment plant effluent B.O.D. Separated ash disposal has been a problem at times due to odors from the ash drying beds. Because the ash dewaters readily without chemical conditioning, a small vacuum filter may be used in the future.

Economics - The cost of wet oxidation as a means of "complete sludge destruction" depends largely on the degree of oxidation desired, the plant size, and the nature of the feed solids. Ettelt and Kennedy reported that the current wet oxidation costs at the Chicago Sanitary District for 70 to 80 percent C.O.D. reduction were $34 to $38 per ton of sludge(56). This cost included capital (interest at %5) and operating figures, but not lagooning or any alternative ash dewatering and disposal processes. It seems reasonable then that the total sludge handling cost at Chicago would be near $40 per ton.

Teletzke recently related wet oxidation costs to C.O.D. reduction. He stated that the capital and operating costs for 70 percent C.O.D. reduction were double those for 25 percent C.O.D. reduction (328). Teletzke described a typical cost for wet oxidation plus ash dewatering as follows:

5% sludge feed, 67% volatile, 1,000 lbs./hour, unknown degree of oxidation

Capital cost = $290,000 with a vacuum filter
$225,000 with sand beds

Operating cost = $4.07/Ton (This included $1.92/Ton for power at [illegible]W; fuel cost = $0.60/million B.t.u. de[illegible]d ash hauling and labor costs were not included. The fuel cost for a 3% sludge feed was $2/Ton and for a 6% sludge feed $0.50/Ton.)

The operating costs for the Blind Brook treatment plant at Rye, New York, have been reported as $26.80 per ton (295). Nearly complete destruction of raw primary sludge was accomplished. A breakdown of the total operating cost shows the following unit charges:

Power = $13.60/Ton ($0.023/KWH)
Chemicals = $ 3.60/Ton
Water = $ 3.60/Ton
Labor = $ 6.00/Ton

McKinley described the Wheeling, West Virginia, wet oxidation capital and operating costs as (318).

1) Installed capital cost = $284,000 for a 5.6Ton/day facility.
2) Operating cost = $19.97/Ton which was broken down as follows:

Power = $6.11/Ton
Chemicals = $4.13/Ton
Fuel = $1.65/Ton
Maintenance = $1.17/Ton
Labor = $6.91/Ton

An insoluble organic destruction of 90 percent was achieved, starting with a raw primary sludge feed of 7.35 percent solids.

Weller and Condon compared the economics of wet oxidation with other sludge disposal processes for the Kansas City, Missouri, sewage treatment facility. They concluded that wet oxidation capital and operating costs would be much higher than for other systems (329). In fact, the capital cost was 97 percent greater than the selected alternative and the operating cost, 54 percent higher.

For "complete oxidation" systems, the average total annual cost for wet combustion would be probably about $42 per ton of dry solids.

Summary - The advantages often claimed for the wet air oxidation process included: (1) flexibility in achieving any degree of oxidation; (2) flexibility in type of sludge handled; (3) production of a small volume of oxidized material that settles rapidly, compacts well, dewaters easily, is susceptible to biologic treatment, and offers few nuisance problems; and (4) operation in a small closed system.

Certain disadvantages are associated with the wet oxidation process. First, odor problems can develop from the off-gases and from lagooning of the ash containing effluent. Air pollution caused by the stack gases can be controlled by catalytic burning at high temperatures, but this is an unknown added expense. Odors from lagooning or sand drying bed operations might best be solved by dewatering the ash in a system that includes gravity separation-thickening followed by dewatering on vacuum filters or in centrifuges. Walters and Ettelt estimated the total cost (capital and operation) of handling the wet oxidation effluent at Chicago in this manner (327):

| Operation | Estimated Cost/Ton |
|---|---|
| Sedimentation-Thickening | $0.27 |
| Vacuum filtration | $0.30 |
| Centrifugation | $1.60 |

Another suggested disadvantage of wet combustion systems is the need for high quality supervision and frequent maintenance. Operating at the high temperatures and pressures required for a high degree of oxidation necessarily involves relatively sophisticated equipment and controls. One operational disadvantage could be the need to recycle wet oxidation liquors back through the wastewater treatment processes. This may represent a considerable organic load and the fine ash could plug air diffusion plates and sludge vacuum filter media.

The major disadvantage of wet oxidation is the cost of construction and operation. Recent studies have shown that this system of solids handling and disposal is the most expensive of those processes often considered in the design of sewage treatment plants. As mentioned previously, the specific cost depends on the required degree of oxidation which in turn depends on factors unique to a local situation such as the size of the plant, the land available for ultimate disposal, and the cost of power (304).

Many engineers believe that wet combustion has the potential of being the best method for ultimate sludge disposal. Further research and development of this technique is certainly warranted.

## F. Burning with Refuse and Miscellaneous Techniques

General - Solids disposal whether refuse or semi-solid wastewater sludges has been an urban problem that becomes more critical as population and manufacturing increases. Perhaps combining all the different solids discarded in an entire urban area, and incinerating them together might be the best eventual procedure. Some data are already available demonstrating successful incineration of refuse and sludge. Los Angeles has been investigating the use of sanitary sewers to transport all waste solids to a central collection point - the sewage treatment plant. They have envisioned the grinding of solid refuse before discharge to the sewers.

For many years, European refuse combustion practice has been to use the refuse as fuel to generate steam or hot water for power generation and heating. Incineration of wastewater sludges in boiler furnaces has been accomplished in the United States. It represented an appealing approach to combustion because the liberated heat is put to useful work.

Combined Refuse-Sewage Sludge Incineration - Many cities incinerate dewatered sewage sludge and refuse in separate units. On the surface, combining the two incinerator operations into one would appear to be economical. Three factors, however, must be contended with in any combined burning process: (1) hauling costs, (2) sewage sludge moisture, and (3) waste production rates which affect uniform blending of the two diverse materials.

Hauling costs often account for most of the operating budget in refuse incineration. Because cities frequently install refuse burners in a central location and sewage treatment plants at one end of town, hauling costs for a combined operation may be prohibitive. This is one reason why the Los Angeles investigation is so interesting.

It was generally thought that sewage sludge must be dewatered to at least 80 percent moisture before combining it with refuse for incineration. Of utmost importance is the maintenance of a uniform low moisture in the feed to a combined incinerator. Various ratios of refuse to sludge for moisture control have been reported (2:1 to 20:1), but the specific level at any one location must have been determined on the basis of sludge type and moisture, heat value of the various solids, type of furnace, operating procedures, and other factors.

Obviously, producing a uniform material for the furnace requires a coordination of the volume of refuse and sewage sludge fed to the blending device. Raw sewage solids are produced continually; refuse availability depends on municipal collection schedules and on the operating schedule of industries producing refuse for disposal. Storage facilities for the solids are necessary, therefore, to assure a uniform mixture.

The literature contained a number of successful examples of sludge-refuse incineration. Whitemarsh Township, Pennsylvania, burned vacuum filtered raw primary and trickling filter sludge with refuse (322, 355). The 75 percent moisture filter cake was combined with refuse at a ratio of 24:1 (refuse to sludge) to produce a mixture with a moisture content only 3 percent greater than the refuse alone. Sewage plant effluent was used to cool the incinerator furnace walls and to scrub stack gases. Excess heat from the combustion process could be used to pre-dry the filter cake. Operating costs were reported to be $3.00 to $6.00 per ton.

Frederick, Maryland, has also successfully incinerated a vacuum filtered raw sewage (70 to 75% moisture) with refuse (28, 355). Effective and economical incineration was possible with a mixture of 2.9 parts refuse to 1 part wet sludge. This ratio must be strictly maintained for adequate operation. Little auxiliary fuel was required due to the large amount of heat released by refuse combustion.

Waterbury, Connecticut, has burned a dewatered sludge with a high grease and fiber content in a refuse incinerator (291). Hot gases from the incinerator were used to dry the vacuum filtered sludge; cool gases were returned for deodorization in the furnace combustion chamber. Operating costs for filtration and incineration were reported as $14.34 per ton (chemicals not included) and capital costs as $8.50 per ton. The total annual cost was, therefore, $22.84 per ton.

Two cities in Wisconsin have incinerated wastewater sludges with refuse, Neenah-Menasha and Kewaskum (306). Neenah-Menasha sludge, mostly papermill waste, was vacuum filtered to 70 percent moisture and heat dried to about 17 percent moisture before incineration in a traveling-grate-type furnace. The furnace feed consisted of 20% garbage (80% moisture), 57% rubbish (10% moisture), and 23% sewage sludge (17% moisture). Operating temperatures were 1,900°F to 2,000°F. Reported advantages were a reduction in hauling costs and the cost of auxiliary fuel that would have been required, if sewage sludge were incinerated alone.

Kewaskum activated and primary sludge also had a high industrial component (milk and malt wastes). It was vacuum filtered and burned with municipal refuse at a temperature of 1,400°F to 1,600°F. No nuisance problems or need for auxiliary fuel have developed. The costs of vacuum filtration and incineration were estimated to be equal to the cost of digestion.

Figure 19.XII illustrates a typical combined sewage sludge-refuse combustion system.

The successful operations described in the preceding paragraphs indicate more consideration should be given to combined refuse and raw sludge incineration systems. It may be particularly useful in small cities where hauling costs could be reasonable. Centrally located refuse collection and sewage treatment could make this system also conducive to larger cities. Or perhaps, some potentially inexpensive refuse collection technique, as is being investigated in Los Angeles, could make combined incineration desirable.

Improved mechanical design would undoubtedly encourage combined incineration. This could include systems to lower the moisture content of sludge feed as well as to break the sludge into small particles and distribute it uniformly throughout the refuse, Certainly using the waste heat from refuse combustion has much appeal; using it to burn or dry sludge deserves more attention.

Burning Sludge as a Useful Fuel - Incinerating sludge in conjunction with a waste heat boiler to use the excess heat in generating steam for heat and power has seemed to be a reasonable approach. At the Chicago Sanitary District, facilities were originally installed that would allow the burning of dried sewage sludge for steam production but this sludge was too valuable as a fertilizer to justify its burning. At Hershey, Pennsylvania, somewhat the opposite was true, because dried sludge appeared to be more valuable as a fuel than as a raw material for grease recovery. The Carver-Greenfield dehydration process was installed at Hershey. It comprised the following steps: (1) sludge disintegration, (2) fluidizing and water separation by the addition of oil, (3) triple stage evaporation, (4) centrifugation, (5) screw pressing, and (6) incineration. The dried sludge (11,000B.t.u./lb)was fed to the boiler furnace at a moisture content of 2.5 percent. A portion of the steam produced was used in the evaporation stages. Supplemental fuel oil was also burned in the furnace.

Figure 19.XII

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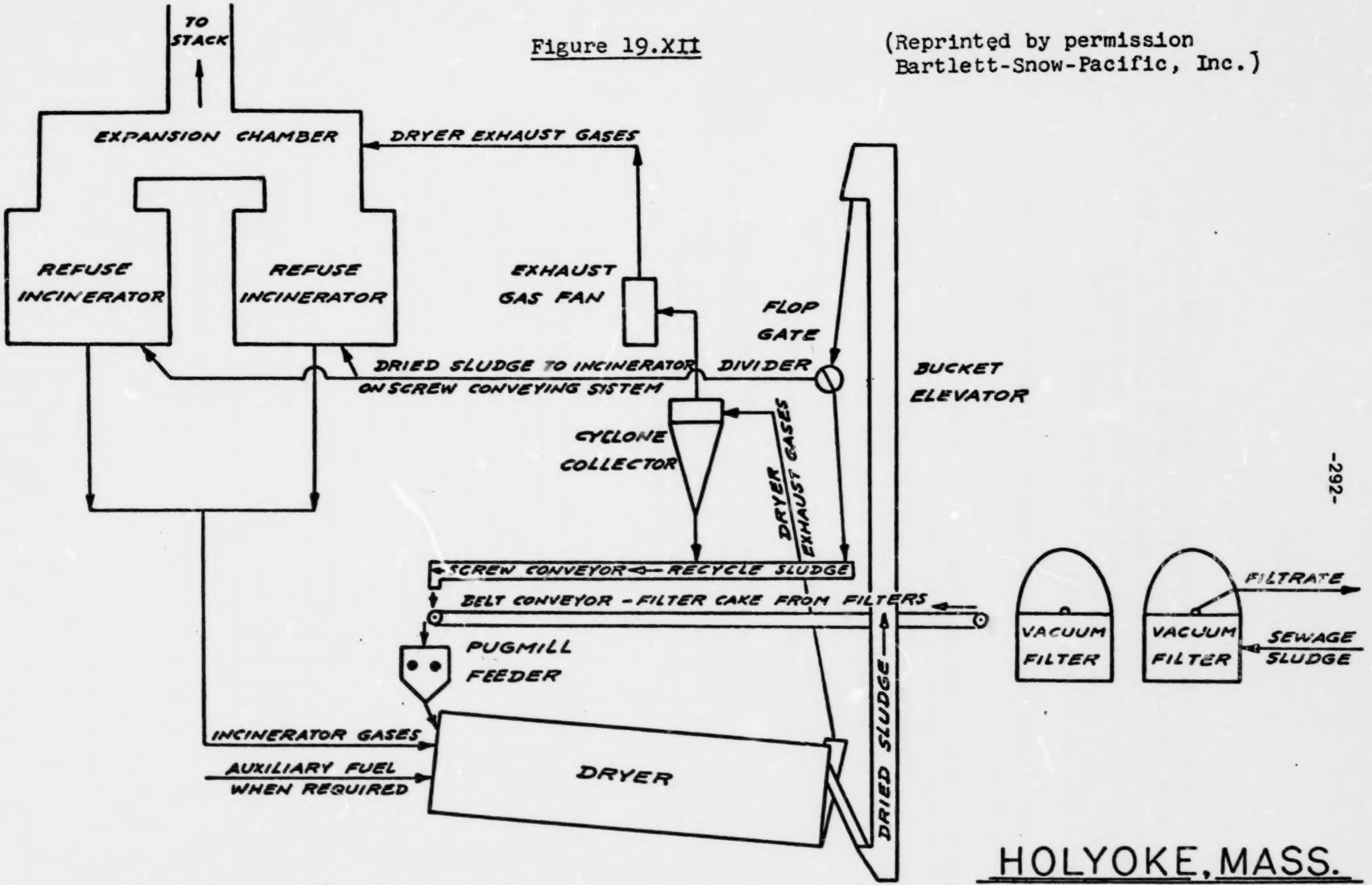
Bartlett-Snow-Pacific, Inc.)


TO STACK
EXPANSION CHAMBER
DRYER EXHAUST GASES
REFUSE INCINERATOR
REFUSE INCINERATOR
EXHAUST GAS FAN
FLOP GATE
DIVIDER
BUCKET ELEVATOR
DRIED SLUDGE TO INCINERATOR ON SCREW CONVEYING SYSTEM
CYCLONE COLLECTOR
DRYER EXHAUST GASES
SCREW CONVEYOR ← RECYCLE SLUDGE
BELT CONVEYOR - FILTER CAKE FROM FILTERS
PUGMILL FEEDER
VACUUM FILTER
VACUUM FILTER
FILTRATE
SEWAGE SLUDGE
INCINERATOR GASES
AUXILIARY FUEL WHEN REQUIRED
DRYER
DRIED SLUDGE

FILTER CAKE : 2000 LBS./HR. DRY SOLIDS
DRYER FEED MOISTURE: 65 TO 75 %
DRYER PRODUCT MOISTURE : 10 TO 20%
INCINERATOR GAS TEMPERATURE : 1100 TO 1400°F
AUXILIARY FUEL: № 4 FUEL OIL

HOLYOKE, MASS.

NEW SLUDGE DRYING SYSTEM
BY BARTLETT - SNOW - PACIFIC, INC.
INSTALLED IN 1964 TO UTILIZE
EXISTING REFUSE INCINERATOR

TIGHE & BOND - CONSULTING
ENGINEERS

A large chemical company has successfully incinerated a thickened waste activated sludge (2.2 to 2.6%) in a boiler furnace along with conventional fuels (332). However, inorganic deposits, accumulated on the boiler tubes, and eventually forced suspension of this disposal technique. It has been suggested that sludge cake could be used as fuel for a gas turbine (66). Sewage sludge may be considered a low grade fuel, but new combustion units tailored to burn this material and recover the waste heat should be investigated.

## G. Summary

As the volume of sludge inexorably increases and land areas become less available and more expensive, incineration becomes a logical and economical process that is being considered and installed by more and more municipalities and industry. While this chapter and others has emphasized sewage sludge, a wide variety of industrial sludges are being incinerated: e.g. chemical sludges, petroleum tars, paunch manure, papermill sludges, etc.

The advantages of incineration include: (1) nearly complete combustion of organics, (2) large reduction of sludge volumes, (3) production of an inert ash that is usually easy to dispose of, and (4) the destruction of microorganisms and potential nuisance-causing materials.

These advantages are achieved in a wide variety of incineration equipment including: (1) multiple hearth furnaces, (2) flash-drying incineration units, (3) rotary kiln incinerators, (4) fluidized sand bed incinerators, (5) atomized spray units, (6) conventional boiler furnaces, and (7) wet combustion units. Multiple hearth furnaces have been the standard units for sewage sludge combustion but fluidized bed units are becoming increasingly popular particularly at small treatment plants. Rotary kiln incinerators are successfully used by industry for burning a wide variety of sludges. Atomized spray units have the appeal of not requiring prior mechanical dewatering of the sludge, but performance and economic data are not very plentiful due to the newness of the system. The wet oxidation process has a number of disadvantages that include cost, complexity, less than complete destruction of organics, and air pollution problems.

One factor in the selection of combustion systems is the solids content of the thickened sludge. Rotary kilns can operate over a wide range of 7 to 70 percent solids. Lower solids levels, such as 2 to 10 percent require fluidized bed, atomized spray, or wet combustion techniques. Sludges with high solids concentrations, 25 to 70 percent, can be burned in simple stationary incinerators (50).

The broad question of whether to adopt incineration or some other sludge disposal technique involves a number of factors including the size of the city or industry, climate as it affects land disposal, land area available and its proximity to residences, proximity to the ocean where sludge dilution may be feasible, and the potential fertilizer market. Incineration is considered to be applicable to cities with population equivalents of at least 10,000. Many engineers believe raw sludge incineration is more economical than digestion followed by land disposal techniques for cities exceeding a population of 20,000.

One fascinating new idea is submerged combustion where sludges are incinerated as they are collected in sludge hoppers of sedimentation basins. Solids handling and disposal would certainly be simplified by eliminating the costly handling steps between clarification and ultimate disposal.

Elimination of at least the mechanical dewatering step similar to the Ashland and Piqua operation would be a forward step for multiple hearth and fluidized bed incineration. To accomplish this, the liquid sludge would have to be consistently thickened to a level greater than the 15 percent accomplished at Piqua. Otherwise, direct incineration of the liquid sludge would be uneconomical.

But, with or without design improvements, incineration is the one sludge disposal process that, without a doubt, has a bright future because it meets future sludge disposal criteria.

## 20. PYROLYSIS

Heat treatment of waste solids by pyrolysis is being investigated as a substitute for incineration. Pyrolysis differs from incineration in that it involves heating without oxygen. The basic purpose is to decompose complex organics to simpler materials. In the case of refuse solids, this may be accomplished at 1,200°F to produce compounds of commercial value such as combustible gas for boiler furnace fuel, elemental carbon, tars, resins, and various acids.

Pyrolysis, like incineration, reduces the sludge volumes and sterilizes the end product. Unlike incineration, it offers the potential advantages of: (1) eliminating air pollution, and (2) the production of useful by-products. Air pollution can be controlled because heating takes place in a closed system that allows the collection of gases for beneficial uses or flaring.

Research on pyrolysis techniques for refuse solids has been underway. Its application to wastewater sludge could be evaluated when the refuse data are available. A major reservation about the pyrolysis approach would appear to be the assumption that by-products could be sold to reduce operating costs.

## 21. HEAT DRYING

General - Any decision to heat-dry sludge includes the assumption that a market exists for the sale of the dried product as a fertilizer or soil conditioner. As discussed in the chapter on Fertilizer, a market often does not exist and, as a result, heat drying has not been given serious consideration by many consulting engineers.

If a thermal disposal process were adopted, due to site limitations or the cost of alternate sludge handling techniques, Quirk recommended resolution of the following questions (65e):

1. What is the difference in cost between drying and incineration systems or combinations of the two?
2. What is a realistic market price for the dried sludge?
3. What market conditions are required to justify heat drying over cheaper alternatives? What is the local interest in heat drying and what public relations value may come from selling dried sludge?
4. What portion of the annual sludge production could be marketed? What is the minimum price that could be expected in a declining market?
5. What additional costs are necessary for deodorization?

A detailed analysis of these questions and their answers generally preclude heat drying processes. Many, if not most, of the heat drying processes installed at sewage treatment plants have been abandoned in favor of incineration or other sludge disposal methods.

MacLaren stated that the installation of a complete heat-drying plant without facilities for burning could no longer be recommended (53). He knew of no example in Ontario where a fertilizer manufacturer had offered to purchase the entire sludge production of a sewage treatment plant. Price quotations may be made, but unless specified in a contract, there is no guarantee that all heat dried sludge will be removed from the plant site.

Equipment - Units to dry wastewater sludges to less than 10 percent moisture include the following types: (1) flash dryers, (2) multiple hearth dryers, (3) rotary dryers, and (4) atomizing spray dryers. Flash dryers have been the most common type in use at sewage treatment plants; industry has used various designs but frequently the choice was a rotary type. Most systems can be made flexible enough to dry or incinerate. Heat drying processes usually have been preceded by a mechanical sludge dewatering step.

Flash drying instantaneously removes moisture from solids by contact with a hot gas stream. The process has included blending wet filter cake with previously dried sludge to lower the moisture level, violent mixing of the semi-dry sludge with hot gases (1,300°F) in a cage mill, and separation of dried sludge from the gases in a cyclone. A portion of the dried material is returned automatically to the mixer for use in conditioning incoming wet sludge. Combustion of fuel in the form of gas, oil, coal, refuse or sewage sludge itself provides the heat for the process. Vapors from the flash drying cycle are returned through preheaters to the furnace where they are heated to 1,200°F to destroy odors. Effluent gases pass through a centrifugal-type dust collector or a wet scrubber, depending on local air pollution control regulations.

The same multiple hearth furnace, conventionally used for sludge incineration, has been adapted for heat drying. Modifications to the basic furnace design included fuel burners at the top and bottom hearths plus down-drafting of the gases. The wet feed sludge was mixed in a pug mill with previously dried sludge. As the solids moved downward through the furnace, the gases became cooler and the solids became drier. At the point of exit from the furnace the gas temperature was about 325°F and the solids temperature about 100°F.

Rotary dryers have been basically long steel cylinders into which hot gases are introduced for drying. As the cylinder revolves at 4 to 8 rpm the hot gas enters at one end along with the dewatered sludge cake. Baffles or flights break-up the sludge as it passes from the inlet to the outlet. Wet sludge is also mixed with previously dried material in a pug mill, similar to other drying units. The complete system includes cyclone dust collection and a gas deodorizing incinerator.

Atomized drying by spraying liquid sludge into a vertical tower through which hot gases are passed downward was a process first patented in 1872. The water is evaporated from the atomized particles and passes off with the hot gases as the dried sludge drops to the bottom of the tower. Dust carried with the hot gases is removed by a dust collector or separator. Atomized drying is a procedure used by many process industries for drying many commercial products.

Performance and Economics - Schenectady, New York, represents one of the very few locations where heat drying of sewage sludge is considered satisfactory. They have sold enough dried sludge as fertilizer to offset a significant portion of their operating costs (315, 379). Digested primary sludge is vacuum filtered to 26.5 percent solids and flash-dried; operating costs are:

Once the decision to incinerate is made, a number of other questions must be considered for each particular situation. Among these are: (1) to digest or not, (2) to mechanically dewater or not, (3) to combine with refuse incineration, and (4) to attempt to recover heat. It seems reasonable not to digest sludge because the raw material has a higher heat value, it dewaters easier than digested sludge, and auxiliary fuel is usually not required. The argument that digestion reduces sludge volumes and produces valuable digester gas is of minor importance compared to other factors.

With multiple hearth and fluidized bed equipment, mechanical dewatering in vacuum filters or centrifuges become an accepted pretreatment step. Mechanical dewatering is expensive, but the use of the large quantities of auxiliary fuel necessary to burn liquid sludge is also expensive and, therefore, not generally given serious consideration.

Incinerating combined refuse and wastewater sludge has been accomplished successfully and should be considered in economic studies of incinerator systems. Using the excess heat available from refuse incineration to dry and burn sludge solids is a desirable approach to economical solids disposal. Recent advances in equipment design and technology make the combination process more suitable than it was previously. In the future, designs will be simpler and the system more easily started and stopped. These improvements will encourage small cities to adopt incineration processes.

An example of possible design improvements was reported by Sercu (308). He described a modified design of a rotary kiln incinerator that was able to burn both solid and liquid wastes having high heat values. The incinerator could handle 81 million B.t.u. per hour of liquid tars, plus 60 million B.t.u. per hour of solid wastes.

Recovering excess heat generated from incineration processes is usually considered uneconomical. However, some units have been installed and operated with the flexibility of generating steam for heating buildings, drying sludge, and producing electric power. Improved heat recovery designs are apparently required to justify the added expense of this equipment.

Substantial improvements in incineration processes have been made, but this area still needs further study and development to reduce costs and to increase thermal efficiency, dependability, and freedom from nuisance (310). Very often the requirement to lower costs eliminates the possibility of accomplishing the other three objectives.

| Heat Drying (315)($/Ton | | |
|---|---|---|
| Labor | $11.12 | |
| Fuel oil (9.78¢/gal.) | 11.90 | |
| Power (1.88¢/kwh) | 4.55 | |
| Bags supplies and services | 4.47 | |
| | | $32.04 |
| **Vacuum Filtration** | | |
| Not reported, assume to be: | $15.00 | |
| | | $15.00 |
| Total operating costs for filtration and drying is, therefore - | | $47.04 |

The City of Schenectady received $27.60 per ton for the sludge fertilizer, so, the net cost of operation would appear to be $19.44 per ton. However, the operating cost of sludge digestion was not included, and this could increase the net operating cost to about $23.00 per ton. Adding on the capital cost for expensive flash-drying equipment with facilities for deodorization increases the total net annual cost figure to a level that is less attractive than the literature indicated.

Quirk made a detailed comparison of the cost of heat drying versus incineration (65e). For a model, he used a medium sized installation (2,530 tons/year) and drying equipment that had the flexibility of functioning as an incinerator. A summary of his cost data showed:

| | Incineration or Drying Equipment | | | | Incineration Equipment | |
|---|---|---|---|---|---|---|
| | Incinerated Sludge | | Dry Sludge | | Incinerated Sludge | |
| | W/ Deodor. | W/O Deodor. | W/ Deodor. | W/O Deodor. | W/ Deodor. | W/O Deodor. |
| Operating cost | 9.82 | 6.60 | 24.90 | 17.50 | 9.50 | 6.36 |
| Capital cost | 12.12 | 11.59 | 12.52 | 11.59 | 9.47 | 9.15 |
| Cost ($/Ton dry solids) | $21.94 | $18.19 | $37.42 | $29.09 | $18.97 | $15.51 |
| Vacuum filtration annual cost | 10.51 | 10.51 | 10.51 | 10.51 | 10.51 | 10.51 |
| Total sludge handling cost ($/Ton) | $32.45 | $28.70 | $47.93 | $39.60 | $29.48 | $26.02 |

A comparison of these costs revealed some interesting facts:

1. High temperature deodorization increased costs of either drying or incineration by at least 20 to 30 percent. Deodorization is commonly required at new installations.

2. Incinerating sludge in a system designed for either drying or incineration would require a 17 percent increase in basic unit costs over a system designed for incineration alone.

3. The cost of heat drying sludge is much higher than the cost of incinerating sludge.

Obviously, a market for the dried sludge must exist at a certain volume and price to justify heat drying.

MacLaren estimated that the cost of heat drying over incineration was at least $8 per ton, due mainly to the fuel required to evaporate the moisture (53). He reported that the cost of equipment varied widely depending on the size of the installation. Generally, though, assuming the capacity is provided in two units or more, he believed that the range was approximately $5 to $10 per ton of dry solids based on a 30-year amortization and 5 percent interest. Operating costs were estimated to be $9 to $15 per ton of solids.

At Baltimore, Maryland, the distribution of operating costs was estimated to be as follows: (1) labor - 24%, (2) sludge combustion fuel - 7.9%, (3) fuel for deodorization - 33.4%, (4) materials - 15.3%, (5) power - 10.3%, and (6) administrative and lab - 9.1% (449).

If a price of $8 per ton on a guaranteed basis for the total production of dried product can be obtained, MacLaren believed that heat drying could be cheaper than incineration. He pointed out, however, that prices obtained in actual operation were lower than those expected during the plant design phase. An example was used where prices of $16 to $18 per ton were quoted for heat dried sludge; yet, a price of only $4 per ton was obtained when the production became available. Zack believed that heat drying should only be considered if a price of $12 or more per ton can be obtained for the dry sludge (28).

Milwaukee, Chicago, and Houston have been selling heat dried activated sludge generally for $12 to $18 per ton. Their operating costs are unknown but at Coral Gables, Florida, the total cost of heat drying was $50 per ton of dry solids (40). Using this figure for the three large activated sludge plants, results in a net capital and operating cost of $32 to $38 per ton. Fifty dollars per ton was estimated to be the average total cost for heat drying in the United States; the range was from $40 to $55 per ton.

The economy of heat drying waste sludges might be improved by using waste heat from refuse incineration. Stamford, Connecticut, used hot stack gases from a refuse incinerator to pre-dry sewage sludge filter cake to a moisture content of 6 to 10 percent. The dried cake was sold as a fertilizer or burned in the refuse incinerators (28). At Louisville, Kentucky, vacuum filtered digested sewage sludge was hauled 6 miles to a city incinerator where it was dried or burned. Waste heat from the burning refuse dried the sludge in flash dryers for fertilizer or further burning in the refuse incinerators (66). Other locations have burned digester gas to produce heat cheaply and lower operating costs. Burning dried sludge in boiler furnaces to produce power and/or heat for sludge dehydration has been another possible way to economize on the drying process.

Summary - Waste sludges have been heat dried in an attempt to improve the economy of sludge incineration. This assumes that the sludge can be sold as a fertilizer or soil conditioner at a good price, an assumption that has been proven false in most cases. The sale of sludge is necessary because heat drying represents one of the most costly sludge handling techniques.

Selling dried sludge as a fertilizer is basically appealing because it represents conservation of a natural resource by returning organics to the land. In addition, heat drying offers the advantages of volume reduction, odor reduction, and the destruction of pathogenic microorganisms. These advantages make land disposal of raw sludge feasible (11). Heat drying is also attractive because it represents a way for ultimate sludge disposal; the sludge is permanently removed when sold as fertilizer.

Many sludge drying operations have been suspended, mainly because of cost. The costs are high basically because it takes about 8,000B.t.u.per pound of product to produce a material with 10 percent moisture from a sludge having 80 percent moisture even at 50 percent thermal efficiency (223). This high production cost coupled with a generally unreliable market results in an uneconomical sludge disposal technique.

Other disadvantages involve control, maintenance and air pollution problems. Air pollution is a serious by-product of heat drying unless expensive deodorizing equipment has been installed. Raising stack gas temperatures to 1,200°F to 1,400°F is costly, a heat exchanger almost becomes an economic necessity. At Baltimore, three operational problems plagued the heat drying process: (1) fires and explosions occurred in the drying system from grease accumulations, (2) storage of dried sludge was complicated because the material compacted and absorbed moisture, and (3) a product of predominantly very fine particles was produced (202). The fine, dusty solids were unacceptable to fertilizer companies. A pelletizing or granulating step seemed necessary. For the year 1980, this step was estimated to add $2.90 per ton to the cost of heat drying (449).

Heat drying of sewage sludge has been rarely seriously considered by consulting engineers. Unlike incineration where auto-combustion is possible, heat drying has usually required the burning of significant quantities of oil, gas, or coal. If drying costs could be reduced and the market value of the dried product increased, heat drying could be economically feasible.

A broad scientific research effort to prove the value of dried sludge as a soil conditioner or fertilizer is needed. This could, of course, increase the market value of the product. Also, lower cost methods of heat drying should be developed. In this regard, combining waste sludge drying with refuse combustion offers the potential of improved economics. The use of food industry sludges as an animal feed or soil conditioner would be enhanced by lower drying costs. Drying without the need for prior mechanical dewatering would be desirable if the overall economics were acceptable. (See the Fertilizer and By-Product chapters for further information.)

## 22. SLUDGE ODOR CONTROL AND DISINFECTION

### A. Odor Control

General - Air pollution control has become a problem of increasing importance at wastewater treatment plants as urban areas have expanded and virtually surrounded plants that were formerly in isolated areas. Public awareness of air pollution has led to increased concern about treatment plant odors. Paradoxically, the solving of a water pollution problem may result in the creation of an air pollution problem. This can, for example, happen when waste sludges are incinerated (339).

At a typical sewage treatment plant odors may emanate from many sources including the following: (1) accumulation of grit, screenings, and skimmings; (2) operation of "sick" digesters; (3) sand bed drying or lagooning of incompletely digested sludge; (4) raw sludge thickening or storage in tanks; (5) vacuum filtration of raw sludge; and (6) incineration or heat drying of sludge. Industrial organic sludges may develop odors from many of the same sources.

Corrective Measures - Eliassen and Vath commented that there are two approaches to eliminating or reducing odor problems (339). Odors can be eliminated at the source, or the odors can be prevented from reaching the atmosphere. The approach taken will depend on the nature of the problem, the economics, and the treatment plant design. The basic requirements for preventing odor are intelligent plant design and good plant operation. Intelligent design can include: totally enclosed units; prevention of sludge septicity by providing adequate sludge hopper designs and flexibility in pumping schedules; digesters that cannot be easily upset; and piping flexibility to allow the addition of well-aerated plant effluent to sedimentation and thickening basins. Location of plants in isolated areas or disguising them by plantings are aids due to the "out-of-sight, out-of-mind" psychology.

Good housekeeping and treatment procedures prevent many odors. Examples of such procedures are (338):

1. Prompt burying or burning of screenings, etc.
2. Regular removal of sludge and skimmings from sedimentation tanks.
3. Discharge of only well digested sludge to sand beds, lagoons, etc.
4. Scientific control of digestion and other unit process operations.

Once odors are emitted, control is generally accomplished by one of five methods: (1) combustion, (2) chemical oxidation, (3) adsorption, (4) dilution, and (5) masking. Masking of odorous gases including hydrogen sulfide, methyl mercaptans, and methyl amines is not a very satisfactory method of control. First, it is not acceptable to many people because they object to the masking agent fragrance. Also, odor masking is often not complete, and the effect is an intolerable combination of sludge odors plus masking agent odors. Effective spraying of masking agents outside on windy days is very difficult at small sludge thickening tanks, and even worse at large lagoon areas. Masking has some uses but at waste treatment plants, it should be limited to temporary emergency situations that improve public relations on hot humid days.

All of the other methods of odor control require the basic first step of odor confinement and collection. Effective confinement requires the covering of grit chambers and sludge blending, storage and thickening tanks. Keeping the interior atmospheric pressure slightly below that of the exterior helps to prevent gas from escaping to the exterior atmosphere. Confinement also implies ventilation in rooms, such as those used for vacuum filtration, where people are working. Once confined the odorous gases must then be collected at a central treatment station.

Combustion as a method of removing odors is promising because it can be complete. But, to produce the principal end products of carbon dioxide, water, and sulfur dioxide is costly. Incomplete combustion can be disastrous because intermediate products may be formed that are more unpleasant than the original odors.

Several combustion techniques are used to destroy odors. It is sometimes practical to discharge the gases into existing furnaces so that no extra costs for fuel are necessary. If, however, there are large volumes of odorous gases requiring complete oxidation, a separate combustion system is desirable. Two systems have been in use, representing high and low temperature combustion.

High temperature odor combustion has been practiced at the San Diego Point Loma sewage treatment plant (349). Gases are collected through a suction blower and supplied to a fume incinerator at zero pressure. The incinerator burns digester gas to attain a combustion temperature of 1,100°F to 1,500°F. A heat exchanger, incorporated into the system, provides about two-thirds of the necessary heat requirement. The stack discharge temperature is about 600°F. Incinerator operation, once started and pre-set at incineration temperature, is automatic.

The use of digester gas at San Diego obviously has had its advantages. High temperature combustion is undoubtedly effective in eliminating odors, but it can be expensive. Fuel requirements and the power requirement for induced-draft fans can result in high operating costs.

Low temperature combustion has been possible by using a catalyst, such as some form of a platinum - metallic screen. Such a catalyst enables combustion to be carried out at a temperature much lower than would be possible without it because it accelerates the combustion reaction. A temperature of 600°F has been commonly used. Natural gas has been often burned as a fuel if digester gas were not available. The operating costs can be very high due to maintenance of the screens and the cost of fuel. However, this process can successfully control odor.

Jaffe stated that two approaches to chemical oxidation of gases were possible: (1) oxidizing the gases in a dry environment or (2) scrubbing the gases with a liquid containing oxidants (347). The first approach commonly used ozone to oxidize the odor causing agents. Ozonation has been a fairly common odor control technique because it is relatively inexpensive and usually effective. It has had the disadvantages of requiring close control for safety reasons, and it may generate odors that are objectionable. Ozone in small concentrations is toxic. Monitoring equipment for ozone is available to maintain the slight residual in the exhaust stack necessary for complete odor destruction.

Chemical oxidants such as chlorine, hydrogen peroxide, and hypochlorite have been used in absorption processes to control odors. The process usually involves a scrubbing tower where odorous gases and trickling liquid pass in a countercurrent fashion, allowing a gradual oxidation of the gases.

At the Midland, Michigan, sewage treatment plant, chlorine was added directly to raw sewage sludge to reduce odors during vacuum filtration (463). The average dosage was 5 to 10 pounds of chlorine per ton of dry solids, added just prior to the chemical sludge conditioning tank. The cost of 30 to 75 cents per ton was more than offset by the reduced flocculent dosage after sludge chlorination.

Ferric salts and lime partially control raw sludge odors during filtration; but, because the sludge is exposed to the filter room atmosphere before conditioning, control is not complete. Lime has often been used to control odors from dewatered sludge applied to land.

At New York City, an experimental scrubber that used a No. 3 diesel fuel oil along with naphthalene (0.55 lb. in 10 gals. of oil) successfully removed odorous gases from sewage sludge storage rooms (345). One gallon of oil could scrub 200,000 cubic feet of air. The spent oil could be used in the diesel engines of sludge barges.

Adsorption of odorous gases on activated carbon and other inorganic materials has been successfully demonstrated. However, carbon adsorption by channeling odorous gases through towers packed with carbon has been expensive. Regeneration of the carbon by heat treatment is required at frequent intervals. Therefore, for this technique to be accepted for sludge odor control, the cost must be reduced.

The use of high stacks and fans to dilute odorous gases with the outside atmosphere has not been a satisfactory odor control technique. It lessens odors in the immediate plant vicinity, but downwind odor problems are bound to develop. High stacks and fans are recommended equipment when used with combustion or chemical oxidation processes.

More and more, design engineers have been asked to provide facilities for air pollution control at wastewater treatment plants. These facilities include the covering and ventilation of many structures. As a result, the cost of waste treatment increases, but odor control is necessary. Well-engineered plants allow the plant operator to do a better job of odor control. Certainly, consulting engineers should always consider odor control in their designs.

Many techniques and materials are available for odor control. All in all, high temperature combustion and ozonation have been the most practical means for waste treatment plants. There has been a trend towards raw sludge handling and away from anaerobic digestion. As a result, odor control will become more critical because raw sludge is not stabilized. Raw sludge has been frequently incinerated; so, the opportunity exists to collect gases from unit processes such as sludge thickening and combust them in sludge incinerators.

New research to find better and cheaper oxidants is desirable. Finding a material that could be added directly to sludges in economical low doses and that could keep the sludge odor-free would be a substantial development.

## B. Disinfection

General - Sewage sludge can be disinfected by heat treatment, chemical treatment, and radiation. Digestion and conventional chemical conditioning prior to vacuum filtration will partially disinfect sludge. Because sewage sludge has been disposed of in a manner that allows contact with people, disinfection to eliminate the public health hazard associated with pathogenic organisms has often been required. The disposal of sludge to the ocean and its use as a fertilizer or soil conditioner involves potential contact with people.

Data - Heat drying of raw sewage sludge is an effective disinfection technique. Data from four large cities selling dried sludge as a fertilizer have shown low bacteria content (334). Based on the relative heat sensitivity of coliform bacteria and enteric pathogens that may live in sewage sludge, it is reasonable to assume that if heat kills the coliform bacteria, the enteric pathogens will also be killed. Because the bacterial, parasitic, and viral enteric pathogens found in sewage sludge have the same order of heat sensitivity as coliform bacteria, the use of heat dried sludge even on vegetables could be considered as safe.

A study of the survival of E. coli in digested primary sludge showed that they survived for 7 weeks at 37°C and for 2 weeks at 22°C. The coliform organisms apparently disappeared because of competition from other microorganisms better adapted to the digestion environment (344). Disease organisms such as typhoid-dysentery bacilli, polio virus, anthrax, ova of parasitic worms, and brucella have been thought to have a rapid mortality rate due to their sensitivity to the unacceptable digestion environment. One study where raw and digested sludge was exposed to 55°C for 2 hours resulted in 100 percent destruction or inactivation of Ascaris Lumbricoides ova (343). Keller reported that thermophilic digestion destroyed all ova of parasitic worms and cysts of amoebae parasitic to man in 24 hours (341).

Digested sewage sludge can be disinfected by chlorine if the sludge is thoroughly digested (342). An actively digesting sludge requires a much higher chlorine dose than a well digested sludge. If sludge and chlorine are thoroughly mixed, the following relationship between chlorine dose and contact time exists:

| Contact Time | Lbs. Active Chlorine/Gal. of Sludge | $/Ton* |
|---|---|---|
| 0.5 hr. | .0334 | 11.90 |
| 1.0 hr. | .0416 | 14.90 |
| 2.0 hrs. | .0500 | 17.85 |
| 3.0 hrs. | .1333 | 47.70 |
| 4.0 hrs. | .1758 | 62.75 |

*Assume a 5% sludge and 7-1/2 cents per pound for chlorine.

Connell discussed laboratory studies of raw primary sewage sludge disinfection using the following chemicals: chlorine, bromine, iodine, calcium and sodium hypochlorite (348). He found that microorganisms were protected by clumps of solids which limited complete disinfection. Homogenizing the sludge in a blender reduced the chemical requirement and increased the sterilizing power. Raw sludge exerts a high chlorine demand; using a 2 hours' contact time the following dosages effectively disinfect a raw sludge having 5 percent solids:

| Chemical | Dose (%) |
|---|---|
| Chlorine | 6 to 7 |
| Sodium hypochlorite | 4 to 5 |
| Calcium hypochlorite | 6 to 7 |

The use of ferric salts and lime to condition sewage sludges before vacuum filtration has often reduced the bacteria population in sludge by at least 50 percent (227), but the remaining bacteria constitute a potential health hazard.

Radiation has been studied as a means of sterilizing sewage sludge. A threshold absorbed dose of $10^4$ rads is necessary before large numbers of the bacteria are inactivated. Apparent sterilization (100 percent kill) was achieved at a radiation dose of 5 megarads per pound (350). The fact that sludge can be sterilized by radiation may be interesting, but the very high costs involved make it impractical.

Summary - Because large quantities of sewage sludge are ultimately used as a fertilizer or soil conditioner, the question of sludge disinfection becomes of vital interest. The opinion has been expressed by numerous people that there is no record of disease transmission to humans as a result of using sludge as a fertilizer. This good record may be a reflection of various health department regulations. It seems logical that pathogenic organisms would not survive through the various sludge handling processes in common use because the environment is so foreign. Heat drying and digestion followed by dewatering and storage seem to produce a material that can be safely used on land for beneficial purposes.

There does not appear to be an urgent need to improve disinfection processes except when such improvement may affect odor control. New techniques for odor control may involve sludge stabilization and, therefore, sludge disinfection.

## 23. WATER PLANT SLUDGE DISPOSAL

General - The disposal of sludges resulting from the clarification and softening of raw water at water treatment plants has not been as much of a problem as wastewater sludge disposal, but it is becoming more critical every day. Two primary reasons have been responsible for the increased concern about water plant sludge disposal: (1) urban areas are growing and less and less inexpensive land is therefore available for land disposal and (2) increased interest in water pollution is restricting the dumping of water plant sludges into surface waters. At many plants, sludge disposal has become a major operational problem. As is the case in waste treatment, the least costly disposal method is the one normally used.

Methods of Disposal and Sludge Characteristics - Black conducted an extensive survey of water plant sludge disposal practices, with the following results (460):

| Method of Disposal | Percentage of Water Plants Using |
|---|---|
| To flowing streams | 58.4% |
| To drying beds or lagoons | 29.6% |
| To storm or sanitary sewers | 8.6% |
| Other methods | 3.4% |

In contrast to waste sludges, water sludges frequently can be disposed of because of their basic nature, by dilution in surface water. Water sludges contain mostly inorganic matter and cause few odor problems even when the raw water has a high concentration of organic material. Softening-plant sludges consist primarily of calcium carbonate with small amounts of ferric, magnesium, and aluminum hydroxide. The sludge particle sizes are very small, most between 5 and 15 microns (460).

It is difficult to predict what the softening plant sludge volumes and the settled sludge solids concentration will be. It is known, however, that 2.5 pounds of sludge (dry) is produced per pound of commercial quicklime added for softening. The concentration of solids in the settled sludge may vary from 5 to 33 percent. Volumes range from 0.4 to 6.0 percent of the water softened (460).

Disposal by dilution into surface waters is simple, inexpensive, and acceptable to many State regulatory agencies without prior treatment. It does not have much effect on the dissolved oxygen content of the receiving waters, but it can be a nuisance because it produces turbidity and forms sludge banks. More and more States are classifying this disposal technique as water pollution.

Lagoon disposal is simple and inexpensive. There is a large land requirement, but low operational costs. Few legal problems have resulted from this disposal method. The lagoon capacity is affected by: (1) whether sludge solids concentration is high or low, (2) whether continuous or intermittent lagoon loading is practiced, (3) whether the supernatant liquid is decanted, and (4) whether the climate is tempered or cold (452). Sludges can be dried to 50 percent moisture in lagoons and then removed.

The lagoon capacity requirement in five midwestern cities (assuming that the sludge was dewatered to 50 percent moisture) was 0.45 to 0.66 acre-feet/year/mgd/100 ppm of hardness removed. According to Howson, multiple basins were desirable so sludge could be air-dried before additional sludge was added (452). He recommended filling to depths of 3 to 5 feet and supernatant decanting so that the sludge was exposed to the air to facilitate drying. Where sludge can be lagooned to 10 foot depths, it is common to provide lagoon land areas of 3 to 5 acres per mdg of water treated.

According to Howson, pipeline transportation of water sludges to lagoons would be simple and inexpensive. Asbestos-cement pipelines (4 to 6 inches in diameter) are adequate and can be constructed at a relatively low cost. It has been estimated that the total annual cost for lagooning water plant sludge from a 10 mgd facility removing 100 ppm hardness would be only $1,250 to $2,500 (452).

Water plant sludge has been occasionally dried on sand drying beds or vacuum filters prior to land disposal. Ultimate disposal may be to landfills or to agricultural land for use as a soil conditioner. At Boca Raton, Florida, the water plant sludge was vacuum filtered and used as a roadway base stabilizer (456). The use of the filter was a tremendous improvement over trying to dewater by dumping the wet sludge into unsightly piles. Dewatering sludge was definitely more expensive than dilution or lagoon disposal, but the operation was fairly simple and the costs were moderate. Some revenue may be secured by selling the sludge to farmers. Sometimes water plant sludge has been sold as a soil conditioner without prior dewatering; the liquid sludge was simply spread from a tank truck used to haul the waste.

At many cities the water plant sludge has been added to the municipal sewerage system. Some observers believe that the sludge functioned as a raw sewage flocculent and thereby improved the overall sewage treatment efficiency (451). If the dumping of water plant sludge is not proportioned over a period of time, it may inhibit biological treatment processes at waste treatment plants.

One interesting and discernible trend in water plant sludge handling has been the increased use of recovery techniques. At locations where dilution and lagooning were not feasible and hauling to distant farmland was not economical, waterworks sludge recovery was an alternative solution to disposal that was sometimes adopted. Sludges from both clarification and softening processes can be recovered.

Alum has been commonly used to clarify raw water at water purification plants. The sludges removed from sedimentation basins at these plants consisted of a dilute suspension of aluminum hydroxide floc containing the substances removed from the water, such as algae and silt. Reclaiming alum (aluminum sulfate) from the hydrous sludge and reusing it for raw water flocculation was possible.

Investigations in England determined that sulfuric acid could be used to convert insoluble aluminum hydroxide to aluminum sulfate, which in turn could be reused as a flocculent (458). The amount of aluminum hydroxide dissolved by the addition of sulfuric acid was a function of the pH of the acid treated sludge. Solubility was very rapid when the sludge pH was less than 4, and about 60 to 65 percent of the alum was recovered when the pH was decreased to about 3. The addition of acid increased the sludge settling rate, its compaction, and its dewatering rate. This phenomenon was apparently due to the release of bound water.

Roberts and Roddy reported that 3.8 pounds of commercial alum produced 1.0 pound of aluminum hydroxide floc which theoretically required 1.9 pounds of sulfuric acid for recovery (453). In a wet process design for Tampa, Florida, they estimated that 1, 183 pounds of 93.0 percent sulfuric acid were needed to produce 2,000 pounds of reclaimed alum (17% $Al_2O_3$) at a 90 percent yield. At Tampa, the cost of commercial alum was $38.08 per ton and sulfuric acid, $19.48 per ton (453). They assumed that $26.59 per ton could be saved by using reclaimed alum.

The above figures must be modified and interpreted in relation to the overall water treatment costs; the recovered flocculent will have a lower efficiency than the origianl commercial alum so higher dosages will be required. Also, recovery is not complete, so some commercial alum must be added.

A typical alum recovery process has consisted of the following unit operations:

1. Collection of the 1.5 to 2.5 percent waste sludge in storage tanks.
2. Acid treatment.
3. Separation of aluminum sulfate by centrifuging or filtration.
4. Pumping the solution to storage tanks.

The recovered alum could be mechanically dewatered and heat-dried, but the added expense seemed unnecessary.

Accurate plant-scale performance and cost data have not been reported for alum recovery processes. Recovery offers potential reductions in chemical costs and in the volume of water plant sludge to be disposed of; however, these advantages must be evaluated in relation to certain disadvantages. These include the high cost of sulfuric acid in some locations, the increased dosage required for recovered alum, the cost of operating a centrifuge, and the need for sludge disposal facilities to be used in conjunction with a recovery process.

Additional research is warranted, but a recovery process that is economically competitive with the other common disposal techniques should not be expected.

Lime recovery processes have been installed at numerous water softening plants. Where lime costs are high, calcining to recover quicklime for reuse in the softening process has, unlike alum recovery, proven to be more economical than purchasing commercial lime and wasting the softening plant sludge.

According to Black, one pound of lime (CaO) produced 3.57 pounds of sludge that can be dried and calcined to recover 2 pounds of lime(460). In practice, 100 percent recovery was not obtained, but, because of the calcium and bicarbonate alkalinity present in the hard water, more lime can often be produced than is required for the softening process.

The basic recovery process included storage-thickening of the clarifier underflow, mechanical dewatering, and calcining. Another step often included before dewatering was recarbonation of the waste sludge. This treatment improved the settling rate and, later, the separation of unwanted magnesium hydroxide from calcium carbonate. The most popular calcining units have been rotary kilns and fluidized beds. Mechanical dewatering was accomplished in vacuum filters or centrifuges. Centrifuges have the important advantage of separating a portion of the magnesium, ferric and silica compounds from the calcium carbonate slurry. Magnesium build-up was also reduced by adopting split treatment procedures where magnesium was precipitated separately from calcium.

In Miami, Florida, lime was recovered by the following steps: (1) gravity thickening sludge to about 25 percent solids, (2) centrifuge dewatering to 66.8 percent solids, and (3) oil-fired rotary kiln calcining at 2,100°F to 2,200°F (451). The capital cost for the recovery plant was $0.8 million and operating costs were $135,910 per year. No lime was purchased; in fact, lime was sold -- the annual gross was $29,000.

San Diego has recovered lime, but, because softening was no longer practiced, the process has been abandoned. Dewatering was accomplished in a centrifuge and calcining in a rotary kiln heated to 2,000°F by burning natural gas. Nine million B.T.U.'s were required per ton of kilned product (454). While the centrifuge rejected some iron and magnesium from the waste sludge, silica remained. A wet cyclone was used to remove the silica before centrifugation. Calcining was done at only one water treatment plant in San Diego but enough lime was recovered to make the city self-sufficient at three water treatment plants, once a production level of 25 tons per day was achieved.

Dayton, Ohio also became a lime supplier rather than a lime purchaser. Sludge was recarbonated with carbon dioxide-containing gases from the calciner, and subsequently dewatered by centrifuges and burned at 2,000°F (455). The recovery plant cost $1.5 million and produced 150 tons per day of pebble lime.

Lansing, Michigan, has been recovering lime from water-plant sludge for 10 years. The process includes recarbonation, centrifuge dewatering and fluidized bed "roasting" (461). In 1957 operating costs for fuel, labor, power, and water were estimated to be $15.50 per ton at a production level of 25 tons per day. Assuming that commercial lime cost $30 per ton, this left a generous margin for capital costs.

Reclaiming lime sludge has been a common procedure at paper mills using equipment similar to that discussed for water treatment plants. Other industrial sludges such as those from the food industry may also be conducive to lime recovery.

Summary - The disposal of sludges from water treatment plants is becoming more of a problem for many of the same reasons as the disposal of wastewater sludges. Simple procedures such as lagooning and dilution are becoming impracticable due to limited land availability and restrictive water pollution control regulations. A pattern similar to the history of wastewater sludge handling and disposal has been established. With the elimination of "easy" techniques, a logical next step has become mechanical dewatering and land disposal. As this method, in turn, becomes impractical, heat treatment will be adopted.

Recovery of softening plant sludges can reduce the overall plant operating costs, but it involves numerous operational problems. First, magnesium should be excluded from the sludge. To some extent, centrifuges accomplish this but often at the expense of solids capture efficiency. Second, split treatment procedures can be adopted but neither calcium carbonate nor magnesium hydroxide flocs settle as well separately as when they are precipitated together. Third, dewatering and calcining equipment requires substantial maintenance and moderate operating budgets. Fourth, sludge reclamation often does not eliminate the need for alternate sludge disposal facilities because not all of the sludge is processed. A final disadvantage results from changing water quality with the seasons. This, of course, means a variable sludge quality which complicates calcining operations.

Inevitably, more and more water treatment plants will adopt lime reclamation processes and alum reclamation. While reclamation has not been enthusiastically accepted, the cost of water treatment has been reduced by varying degrees at those locations where it has been in operation. Additional research should be undertaken to improve chemical and mechanical procedures so that costs are reduced, efficiency improved, and controls simplified. The complete water treatment plant should be designed with reclamation in mind if the process might be adopted.

## 24. SUMMARY OF SLUDGE HANDLING AND DISPOSAL ECONOMICS

General - Fleming quoted an appropriate statement concerning sludge, "The man who owns the most of it is the worst off" (24). While sludge does have some fuel and fertilizer value, it is a definite liability at any sewage treatment plant.

A specific system to treat and dispose of the sludge should be selected only after all the factors have been scientifically studied. A good system for one location may not be applicable somewhere else because local conditions vary greatly. Weller and Condon stated that the major factors in selecting a sludge processing system were: (1) plant location, (2) plant operation, and (3) economic evaluation (329).

Plant location and operation factors are affected by the climate, physical environment, esthetics, system complexity and efficiency, and the characteristics of the waste. The economic evaluation includes a consideration of relative capital and operating costs and the plant operating agencies' capabilities and desire to meet these costs (329).

Data - Numerous comparative economic studies of sludge treatment processes have been reported in the literature. These studies are useful as general information but the data are applicable only to the specific location and conditions under consideration.

Again, a separate and complete economic analysis is required for each particular treatment plant system. The usefulness of economic data are often nullified by the lack of uniformity in accounting and reporting procedures, but if the data are generated by reliable consulting engineers they can be accepted as being fairly accurate.

Each chapter in this report has included a discussion of the economics of specific sludge handling and disposal processes. This chapter reviews and summarizes the economic data.

A few literature references presented a general review of sludge treatment costs. These include the following:

1. Weller and Condon compared relative costs for sewage sludge treatment at Kansas City (329).

| System | Original Cost | Annual Cost |
|---|---|---|
| Dewatering and incineration of raw sludge | 1.0 | 1.0 |
| Digestion, mechanical dewatering and landfilling | 1.05 | 1.41 |
| Digestion, mechanical dewatering and incineration | 1.43 | 1.38 |
| Wet combustion | 1.97 | 1.54 |

2. In England, the Ministry summarized sewage sludge treatment costs (70). (Average figures reported were arbitrarily increased by 50% to account for increased costs for labor, equipment, etc. in England. Mixed sludge refers to a combination of primary and biologic sludge.)

| System | Disposal Cost ($/Ton) |
|---|---|
| Lagooning raw mixed sludge | 3.15 |
| Free distribution of liquid digested mixed sludge | 8.00 |
| Barging raw primary sludge to sea | 8.40 |
| Air drying digested mixed sludge to 65% moisture | 8.84 |
| Landfilling raw liquid sludge | 10.10 |
| Air drying raw mixed sludge to 65% moisture | 10.10 |
| Filter pressing raw primary sludge to 60% moisture | 11.15 |
| Filter pressing and heat drying secondary sludge | 19.75 |
| Air drying mixed digested sludge to 15% moisture, granulating and bagging | 22.30 |
| By-product recovery of grease from raw primary sludge | 31.15 |
| Filter pressing and heat drying digested elutriated primary sludge to 35% moisture, granulated and sold in bulk | 32.60 |

3. Dietz presented data showing the economy of using digesters at small sewage treatment plants (46). (Annual costs were increased by 25% in accordance with the Engineering News Record (ENR) Cost Index Increase.)

| Population | 6,500 | 10,000 | 20,000 | 30,000 | 40,000 |
|---|---|---|---|---|---|
| System | Annual Cost in Dollars | | | | |
| Digesters with sand beds | 5,700 | 7,700 | 13,580 | 19,300 | 25,250 |
| Digesters with lagoons | 4,765 | 5,700 | 9,100 | 13,700 | 20,500 |
| Vacuum filtration of raw sludge | 9,600 | 10,400 | 14,400 | 18,650 | 24,650 |

4. Logan surveyed construction costs for sludge treatment at small sewage treatment plants (60). (His figures were increased by 18% to account for the change in the ENR Index.)

| System | Construction Cost ($) | | |
|---|---|---|---|
| Plant Size | 1 mgd | 5 mgd | 10 mgd |
| A. Vacuum filtration of raw primary sludge | 52,800 | 76,000 | 152,000 |
| B. Vacuum filtration of raw pri. + sec. sludge | 56,600 | 150,500 | 227,000 |
| C. Digestion and sand bed drying | 98,300 | 397,500 | 812,500 |
| D. Digestion and vacuum filtration | 131,500 | 389,000 | 693,000 |

The above figures were based on a digester design capacity of 3 cubic feet per capita, a sand bed capacity of 1.25 square feet per capita, and a vacuum filter rate of 6 pounds per square foot per hour.

A general review of all available economic data including the recent studies completed for Baltimore, Maryland; Washington, D.C.; and Philadelphia, Pennsylvania (see the Ocean Disposal chapter) yielded the average sludge handling and disposal costs listed below. Most of the data used to compile the average figures were based on sewage sludge processing costs. Industrial sludge treatment costs could vary considerably from the average figures because of their different characteristics.

1. Ultimate disposal (includes cost of preparation, such as dewatering, digestion, etc., as described specifically in item 2).

| System | Capital and Operating Costs ($/Dry Ton) Average | Range |
|---|---|---|
| A. Composting | Not accurately known | |
| B. Heat drying* | 50 | 40-55 |
| C. Incineration | | |
| (1) wet combustion | 42 | - |
| (2) multiple hearth and fluidized bed | 30 | 10-50 |
| D. Landfilling dewatered sludge | 25 | 10-50 |
| E. Disposal as a soil conditioner w/o heat drying* (dewatered) | 25 | 10-50 |
| F. Disposal on land as a liquid soil conditioner* | 15 | 8-50 |
| G. Lagooning | 12 | 6-25 |
| H. Barging to sea | 12 | 5-25 |
| I. Underground disposal | Unknown, potentially inexpensive | |
| J. Pipeline to sea | 11 | |

*Gross cost, does not account for money received from sale of sludge.

2. Sludge handling (specific process costs)

| System | Capital and Operating Costs ($/Dry Ton) Average | Range |
|---|---|---|
| A. Thickening | | |
| (1) gravity | - | 1.50 - 5 |
| (2) air flotation* | - | 6 -15 |
| (3) centrifugation* | - | 3 -20 |
| B. Dewatering | | |
| (1) vacuum filtration | 15 | 8 -50 |
| (2) centrifugation | 12 | 5 -35 |
| (3) sand bed drying | - | 3 -20 |
| C. Anaerobic digestion | - | 4 -18 |
| D. Elutriation | - | 2 - 5 |
| E. Lagooning | 2 | 1 - 5 |
| F. Landfilling | - | 1 - 5** |
| G. Pipeline transportation | 5 | *** |
| H. Liquid sludge disposal on land as a soil conditioner | 10 | 4 -30 |
| I. Heat drying | 35 | 25 -40 |
| J. Incineration | 20 | 8 -40 |
| K. Barging to sea | 10 | 4 -25 |

*Varies tremendously depending on the need for chemicals

**Long hauls would be higher

***Moderate distances, cost varies with length.

A review of the above costs and the general literature on sludge handling and disposal economics led to the following conclusions:

1. Anaerobic digestion of sewage sludges for all small cities and cities located near the coasts is justified. It allows relatively inexpensive final disposal methods such as ocean dilution, lagooning, and spreading liquid sludge on land as a soil conditioner.
2. Lagooning industrial sludges isan inexpensive disposal technique.
3. Pipeline transportation of sludge to desirable disposal areas should be considered because it is relatively inexpensive.
4. If heat dried sludge can be sold as a fertilizer for about $15 per ton, only then should the process be considered.
5. Digesting sludge before incineration cannot be justified on the basis of economics.
6. Water plant sludges are normally disposed of very inexpensively in sewerage systems, lagoons, or surface waters.

Obviously, sludge treatment costs vary greatly. This statement is valid even though two similar treatment plants use identical sludge treatment processes. For this reason, design engineers should make comparative studies and cost estimates for each particular sludge disposal situation. The fact that sludge handling and disposal represents 25 to 50 percent of the total treatment plant capital and operating cost justifies a thorough economic evaluation.

## 25. FUTURE APPROACHES

General - One obvious and general statement that can be made concerning a new approach to sludge handling and disposal is that it deserves more attention from researchers, design engineers, and others involved with water and waste treatment.

To start with, attention could be gained by scheduling national conferences, similar to those convened for solid waste disposal, to discuss thoroughly the problems and their possible solutions among a variety of interested parties. In fact, joint conferences concerning all types of waste solids, whether they be car bodies, garbage, or wastewater sludges, should be called because joint treatment and disposal of all of the waste solids in a particular watershed may be the best solution to individual disposal problems.

Another useful initial step would be to standardize accounting and reporting procedures in the sanitary engineering field. The lack of uniformity today makes it very difficult for researchers, design engineers, and plant operators to compare cost and performance data. Uniformity will enhance the scientific and orderly development of technical procedures in the water and wastewater treatment field.

New approaches to sludge handling and disposal should concentrate on minimizing the number of process steps. Submerged combustion of the sludge in the initial collection basin would represent the ultimate development in this regard. Numerous sewage treatment plants have incorporated multiple process steps between sludge collection and ultimate disposal; including thickening, digestion, elutriation, and dewatering. Incomplete solids capture has been the usual situation in all of these treatment steps. Water pollution has been increased along with waste treatment costs because the "uncaptured" solids were recycled but not totally removed from the waste stream.

Better analytical tools are needed to control sludge handling processes. To start with, a sludge characterization study would be useful; it would provide more data about the fundamental nature of sludge particles and how this nature may be altered to permit more effective dewatering. New instrumentation to control precisely various sludge treatment operations could reduce costs of wastewater treatment and operator frustration.

Because labor often accounts for two-thirds of the operating cost of sludge handling processes, systems and equipment should be designed to maximize the efficient use of labor in order to reduce costs. Improved design of all types of equipment is continually desirable. The improved designs have already resulted in lower costs and the use of mechanical equipment at treatment plants with volumes formerly considered too small to justify mechanization.

Research into methods of reducing sludge volumes should be supported. This is particularly important where biological sludges are involved because their hydrous nature resists dewatering. Perhaps a biological wastewater treatment system could be designed that minimizes the sludge volume while still maintaining efficient B.O.D. removal.

To encourage research into new approaches to sludge handling and disposal, government financial support should continue to be made available. Research and demonstration contracts should continue to be awarded to private industry having specialized knowledge in certain areas of sludge treatment, to operators of treatment facilities having well-qualified staffs, and to university research groups. Water Pollution Control Administration Laboratories should, of course, also continue to take an active role in investigating new techniques.

Specifics - Individual sections of this report include specific recommendations for new research and development. The following are particularly important:

1. Better separation of grit from organic solids; in order to optimize digestion and incineration operations. The hydrocyclone is a step in the right direction.

2. Improved solids concentration and freshness from sedimentation units. Pre-aeration and the use of polymeric flocculents have accomplished this to some degree. New sedimentation basin designs might be a partial answer.

3. Improved techniques for thickening sludge, particularly to a level that would allow economical incineration without mechanical dewatering.

4. Thorough evaluation of aerobic digestion parameters, economics, and sludge dewatering characteristics.

5. Improvements in the anaerobic digestion process. A process is needed that is more stable, produces a clean supernatant liquor or none at all, produces an easy-to-dewater sludge without elutriation, and removes nitrogen and phosphates. "Densludge" thickening, ahead of digestion as practiced at New York, is a good example of how the process may be improved. An evaluation of the effects of detergents on digestion is in order because numerous operators believe this material has a deleterious effect on the process. Continuation of the high temperature digestion studies started at Los Angeles is in order.

6. Means of separately treating digester supernatant liquor alone or in combination with thickening tank effluents, elutriates, centrates, and filtrates. The addition of lime or some other chemical to produce a useful fertilizer would take advantage of the nutrients concentrated in digester supernatant liquor. Studies are needed to supply information on the nitrogen and phosphate content of filtrate, centrate, elutriate and digester, and thickening tank supernatant liquor.

7. Better means of mechanically removing dried sludge from sand drying beds and improved techniques for liquid decanting.

8. Thorough evaluation of the economics of pipeline transportation of various sludges. Research into methods of fluidizing sludge to be pumped through pipelines would be desirable as would the control of septicity.

9. Evaluation of underground disposal techniques for liquid sludge to include deep wells and discharge into abandoned mines, etc.

10. Support of studies showing the effects on aquatic plants and animals of dumping sludge into the ocean.

11. Continued efforts to develop more active chemicals for conditioning sludges prior to mechanical dewatering and simpler, more effective dewatering units. Chemicals that would eliminate the elutriation process would be welcome in the field.

12. Greater research emphasis on sludge conditioning by heat treatment. Perhaps waste heat from incineration processes can be used for this purpose.

13. A broad, thorough and scientific study of the value of liquid, composted or dried sludge as a fertilizer or soil conditioner. This study is long overdue. Some studies are underway, but they should be expanded.

14. Investigation into by-product use of some industrial waste sludges. This might include an inexpensive method to dry food-industry sludges so the material could be used as an animal feed or soil conditioner.

15. Expanded research investigations into sludge combustion techniques. Such studies are justified because combustion is the one disposal method that will meet future criteria. Improvements in the following areas should be considered:

    (a) Incineration of liquid sludge so mechanical dewatering can be eliminated.

    (b) Combustion of wastewater sludges with refuse.

    (c) Combustion of sludge in boiler furnaces to develop steam.

    (d) Heat recovery to distill sewage effluents, condition sludges, etc.

    (e) Combustion of skimmings and screenings.

16. Continued support for the Los Angeles investigations of combining the collection of refuse and sewage sludge by grinding and adding the refuse to the sewerage system.

17. New analytical tools to enable digester troubles to be predicted and to proportion sludge conditioning chemicals to the precise sludge demand. These would be well received by budget supervisors and overburdened plant operators.

18. Investigation into improved methods for odor control.
19. Evaluation of the use of compost or liquid digested sludge to reclaim barren strip mine areas.
20. Continued efforts to develop better methods for reclaiming alum sludges from water treatment plants.
21. Increased evaluation of the feasibility of separate treatment and disposal of primary and secondary sludges.
22. Improved laboratory bench techniques and larger scale tests for developing sludge handling design criteria.

The cost and troublesome nature of existing sludge handling and disposal processes warrant a large research effort. In the future, the situation could be more critical if new techniques are not developed because sludge volumes are rising and increased wastewater treatment efficiencies are producing more difficult-to-handle sludge. Once new and reliable technology is generated, it is important to disseminate it throughout those groups involved in water and waste treatment so that an early effort can be made to solve sludge treatment problems.

THE MENTION OF PRODUCTS OR MANUFACTURERS IN THIS REPORT DOES NOT IMPLY ENDORSEMENT BY THE FEDERAL WATER POLLUTION CONTROL ADMINISTRATION, U.S. DEPARTMENT OF THE INTERIOR.

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